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OPTICAL PUMPS FOR LASERS

Lowell Noble, et al

ILC, Incorporated

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OPTICAL PUMPS FOR LASERS

TRI-ANNUAL REPORT No. 2

By

LOWELL NOBLE AND C. B. KRETSCHMER

AUGUST 1972

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Useful light output is increased by reducing the bore diameter, increasing the filling pressure, and operating with a simmer discharge. A small simmer discharge at one end of the lamp was about as efficient as one running the whole length of the lamp.

Reproducibility of useful light output was $\pm0.4\%$ (average deviation among shots on a single lamp, and $\pm1.2\%$ among lamps in which variations in bore diameter were held within $\pm1.25\%$.

Useful light output of lamps with clear fused quartz envelopes decreased 15% during the first million pulses and remained nearly unchanged during the next nine million pulses. Lamps with High-purity fused quartz envelopes decreased in output by only 4% during ten million pulses.

Preliminary measurements on lamps for pumping holmium lasers indicated that xenon flashlamps are the most suitable for this purpose.

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FOREWORD

The work reported herein was accomplished under Contract Number DAAB07-71-C-0239 for the Gaseous Electron Devices Team, Beam and Plasma Device Technical Area of the Electronic Technology and Devices Laboratory, U. S. Army Electronics Command, Fort Monmouth, New Jersey, under the guidance of Mr. Norman Yeamans, the contracting officer's designated representative.

The studies being carried out on this program are being performed in the Engineering Division of ILC, which is under the direction of Dr. Leonard Reed. Martin Marietta is responsible for the laser effort on a sub-contract basis.

Mr. Lowell Noble is the principal investigator, assisted by Dr. Carl Kretschmer. Mr. Robert Maynard and Mr. Harry Flentz are carrying out the optical measurements and data reduction.

Mr. Paul Rushworth of Martin Marietta is responsible for laser testing.

1.0 SUMMARY AND CONCLUSIONS

1.1 Summary

Work is being carried out to increase the overall efficiency (to 4%) and the reproducibility of light output (to ±5%) of a pulsed Nd:YAG laser that uses a 2.125 inch arc length, 10 joule pump lamp. These results will then be applied to improving the overall efficiency and reproducibility of another pulsed Nd:YAG laser that uses a 1 inch arc length, 5 joule pump lamp. These performance objectives are to be attained by improving the lamps, the driving circuits, and the laser cavities. The best performance obtained before the start of this program was a laser efficiency of 2.32%, using a 10 joule flashlamp with a 3 mm bore and an arc length of 2.125 inches, filled with krypton to 1500 Torr. The flash duration was 60 microseconds.

During this reporting period a number of approaches intended to increase the efficiency and reproducibility of flashlamps for pumping Nd:YAG lasers were investigated, and the results are summarized in this section.

Xenon-filled lamps with cerium-doped quartz envelopes were constructed and tested. The cerium-doped quartz fluoresces and is expected to convert part of the ultraviolet output of the lamp into radiation in the pumping bands. The light output in the 0.40-0.65μm region was higher for the lamp with a fluorescent envelope than for a standard lamp, but the amount of useful pumping radiation, as measured by the fluorescence excited in a sample of laser material, was decreased. The reason may be that the cerium absorbs more useful pumping radiation in the 0.7-0.9μm region than the additional radiation in the 0.40 to 0.65μm region contributes to pumping. Cerium doping in the quartz envelope is beneficial, however, in that it absorbs all radiation below 0.30μm and thus prevents degradation of organic coolants, laser rods, and cavity reflecting surfaces, by ultraviolet radiation.

The use of a fluorescent dye solution in a jacket surrounding the lamp was also investigated. The useful light output was increased by as much as 15% for a clear fused quartz envelope lamp by this means, but the dye was bleached rapidly by the ultraviolet light from the lamp, and became ineffective in relatively few pulses at the 10 joule energy level.

The useful light output of xenon and krypton lamps was found to increase as the bore diameter was decreased from 4 to 2.5 mm. Below this diameter there was little further effect. It was also found that the useful light output increases with filling pressure and is still increasing at 4500 Torr, the highest pressure tested. However, triggering becomes difficult at pressures above 1500 Torr.

The use of a continuous low-current (100-200mA) simmer discharge has been previously shown to increase the efficiency of flashlamps by about 25%. During this reporting period it was found that the simmer current could be reduced to 20 mA and still give a 20% increase in flashlamp efficiency. For a lamp operating at 10 joules per pulse and 20 pps with a 20 mA simmer discharge, this 20% increase in efficiency over non-simmer operation is obtained at the cost of expending about 5% of the total input power in the simmer discharge. About half of this power is expended in the discharge itself and the other half in the series ballast resistor.

It was found that a simmer discharge operating between two electrodes at one end of the lamp is just about as effective as a simmer discharge running the whole length of the lamp in increasing the efficiency of the main pulse. This fact is evidence in favor of the hypothesis that one effect of the simmer discharge is to emit vacuum ultraviolet resonance radiation which builds up a population of metastable atoms throughout the volume of the lamp.

Useful light output measurements on a single lamp, using the digitized fluorescent analysis instrument, had a shot-to-shot average deviation of 0.4% or less. This includes both the actual variability of light output between shots and the random errors of the instrument. A batch of lamps was constructed from tubing selected to be within a range of $\pm 1.25\%$ in bore diameter, and the average deviation in useful light output measurements for single lamps in this batch from the mean for the batch of 28 lamps was 1.17%. Another batch of 12 lamps was constructed from tubing that had been shrunk down on a precision-ground tungsten mandrel, giving tubing within a range of $\pm 0.63\%$ in bore diameter. Single lamps from this batch had an average deviation of 0.78% in relative useful light output.

Life tests on 10 lamps made from selected clear fused quartz tubing showed that the useful light output decreased by 15% during the first million pulses (10 joules, $100\mu s$, 20 pps) and remained virtually constant during the next nine million pulses. Two thirds of the initial 15% decrease is probably due to the formation of color centers that recombine on heating. Lamps made of high purity quartz decreased in useful light output by only 4% during 10 million pulses.

Preliminary measurements of useful light output from Ho:YLF laser material indicated that a xenon flashlamp is probably the most efficient pumping source for pulsed Ho:YLF lasers.

1.2 Conclusions

1. The use of fluorescent cerium-doped quartz envelopes decreases the useful light output of flashlamps, but retards the degradation of ultraviolet-radiation-sensitive laser head components.

2. A fluorescent dye solution in a jacket surrounding a flashlamp operating at 10 joules first increases the useful light output by as much as 15%, but the dye is bleached and rendered ineffective in relatively few pulses.

3. Useful light output increases as the bore diameter is reduced from 4 mm to 2.5 mm.

4. Useful light output increases with filling pressure up to 4500 Torr, the highest pressure tested.

5. A 20% increase in flashlamp efficiency can be obtained by using a simmer discharge that dissipates only 5% of the total input power, when the lamp is operating at 10 joules per pulse and 20 pps.

6. A small simmer discharge at one end of the lamp is about as effective as a simmer discharge running the whole length of the lamp.

7. The average fractional deviation in useful light output of individual flashlamps from the mean for a given group of lamps is approximately equal to the average fractional deviation in bore diameter. If the bore diameter is held within $\pm0.63\%$ by using tubing shrunk down onto a precision ground mandrel, the average deviation in light output is 0.78%.

8. The light output of flashlamps made from clear fused quartz tubing decreases by 15% during the first million pulses, and remains relatively unchanged during the next nine million pulses.

9. The light output of flashlamps made from high-purity fused quartz decreases by only 4% during 10 million pulses.

10. A xenon flashlamp is probably the most efficient pumping source for pulsed Ho:YLF lasers.

2.0 INTRODUCTION

The purpose of this program is to increase both the efficiency and the reproducibility of Nd:YAG lasers through improvements in lamps, in their associated power supplies, and in laser cavities. This work follows a previous contract,(1) which was initiated to improve the efficiency of optical pumps for Nd:YAG lasers used in lightweight man-portable laser illuminators and target designators.

2.1 Objectives

Improved laser performance is sought for four types of laser operating modes, each of which requires the development of a distinctly different pump lamp. A feasibility study of "Optical Pumps for Holmium Lasers" was substituted for a third mode of operation. Table I gives the specifications and performance goals for the four modes of operation.

2.2 Approach

The execution of the Nd:YAG optical pump program is divided into two tasks. The first task is to increase laser output efficiency and, if necessary, lamp life. The second task is to determine the reproducibility of lamp and laser output before and during life tests and, if necessary, improve lamp reproducibility. Another task is to lower threshold requirements and simultaneously increase laser output efficiency of Ho:YLF lasers through optical pump improvements.

The approach to increasing laser efficiency involves:

1. Obtaining a more detailed understanding of the plasma discharge process in the pump lamp and of the effects of bore diameter variation, pressure variation, and mode of operation, on light output.

2. Incorporating new envelope materials, fabrication processes and triggering wire fabrication techniques into the manufacture of lamps. Each may incrementally add to pump lamp efficiency.

TABLE I

Nd:YAG LASER PROGRAM GOALS

	MODE I	MODE II	MODE IV	MODE IV-A
OPERATING CONDITIONS				
Energy Input (Joules)	5	10	5	5
Repetition Rate (pps)	1	20	20	20
DIMENSIONAL CONSTRAINTS				
Laser Rod OD (mm)	3	6	6.35	6.35
Laser Rod Length (mm)	30	63.5	63.5	63.5
Lamp Overall Length (mm)	63.5	(none)	(none)	(none)
PERFORMANCE OBJECTIVES				
Lamp Life (pulses)*	10^6	10^7	10^7	10^7
Initial Lamp-to-Lamp Reproducibility	$\pm 5\%$	$\pm 5\%$	$\pm 5\%$	$\pm 5\%$
Overall Laser Efficiency	2.5%	4%	3.5%	3.5%
Cooling	None	Liquid	Liquid	Compressed Nitrogen Gas

*Laser life is defined as the number of pulses at which the output has dropped by 20% of its initial value.

3. Improving the energy delivery from the PFN (Pulse forming network) by:

   a) Improving PFN-to-lamp matching design techniques that are applicable when the arc does not fill the bore.

   b) Developing new matching circuits.

4. Modifying the laser cavity designs to accept:

   a) the new lamps

   b) new triggering techniques

   c) other cavity improvements

The second task, improving lamp reproducibility, requires very precise measurements of lamp light output. Such measurements have required improvements in existing instrumentation.

The reproducibility of laser output may be improved by:

1) Using lamp materials that are specified to closer dimensional tolerances.

2) Maintaining a closer control over the gas filling and other manufacturing processes.

3) Introducing new triggering methods, power supply concepts and laser cavity changes that can improve reproducibility.

The laser output measurements are being made principally by Martin-Marietta and also by other laser manufacturers. The amount of expensive in-laser testing required is reduced by the use of a recently developed instrument that directly measures the "useful" light that a pump lamp emits, i.e., the light that can be used to pump the excitation bands of the Nd:YAG laser.[1] This device is called a differential fluorescence analysis instrument, and the useful light output is measured in terms of a fluorescent output voltage (FOV). The useful light output must be measured with a high degree of precision in order to determine lamp-to-lamp light output reproducibility. Consequently the existing differential fluorescence analysis instrument has been improved to provide greater precision.

A statistical approach to the measurement of lamp light output reproducibility is being undertaken. Flashlamp life tests have been carried out with five lamps at a time. Mean light output and average deviations have been determined.

For the other task, preliminary measurements were made of the effectiveness of xenon and pulsed alkali metal vapor lamps in pumping Ho:YLF laser material.

3.0 BACKGROUND

Work carried out under a previous optical pump contract[1] resulted in the efficiency improvements shown in Table II and Figure 1. The basis for the efficiency comparisons was the performance of the standard lamp employed for target designator and illumination applications prior to the investigation (a 450 Torr xenon-filled lamp having a 4 mm bore diameter and a 2.125 inch arc length) which uses an external trigger wire for initiation and does not employ simmering.

The simmering of the lamp at a low power level between pulses was first introduced by Yeamans and Creedon as a means of improving lamp life;[2] however, it was later found to significantly increase laser output efficiency.[1] The increase in laser efficiency that resulted from employment of the simmer mode of operation is approximately 25% at the 10 joule input level. A "pseudo-simmer mode" of operation was subsequently developed to provide the increased efficiency while reducing the weight of the power supply required. This technique involves prepulsing the lamp for a period of approximately 100μs before the main pulse is initiated and shows a 15 to 20% increase in laser output.[1] The simmer and pseudo-simmer modes are being further investigated during this program.

TABLE II

IMPROVEMENT IN USEFUL OUTPUT

Averaged Values @ 60 Microsecond Pulses*

Improvement	FOV 5 Joule	FOV 10 Joule	LASER OUTPUT 5 Joule	LASER OUTPUT 10 Joule
Xe to Kr	10%	0%**	29%	10%
450 Torr to 3000 Torr	43%	17%	26%	12%
4 mm to 3 mm	4%	4%	23%	12%
External Trigger to Simmer Mode	63%	25%	62%	30%
Expected Improvement if all effects are independent	168%	52%	225%	81%
Measured Improvement	(not measured)	56%	240%	72%

*The comparison is made at this pulse length because this is the pulse length at which the laser data were taken.

**Improvements are noted for longer pulse lengths (see text and figures).

Figure 1 shows the laser output for 2 lamps operating between 4 and 10 joules energy input. In the case of the 3000 Torr krypton, 3 mm bore lamp, the laser efficiency is 1.7% at 5 joules and 2.05% at 10 joules, using the full simmer mode of operation. Subsequent laser data obtained at International Laser Systems, Inc., with an improved laser cavity gave a laser efficiency of 2.32% at the 10 joule level, with a 1500 Torr krypton, 3 mm bore lamp and external trigger initiation.[1] Accordingly, it would appear that with full simmer operation, efficiency approaching 3% should be realized at the 10 joule lamp energy input level with a 3 mm bore, 3000 Torr krypton lamp.[1]

4.0 EFFICIENCY IMPROVEMENTS

Several modifications of lamps, cavities, coolants, and mode of operation were tried to increase the efficiency of light output in the useful pump bands. All of the modifications were tried with lamps designed for use with the Mode II operation. The fluorescence analysis instrument was used for all tests to measure the useful light output.

The variations included:

1) Use of fluorescent envelope material (cerium-doped quartz).

2) Use of fluorescent dyes in liquid coolants to convert ultraviolet radiation to wavelengths that match the Nd:YAG excitation bands.

3) Effects of smaller bore diameters.

4) Effects of increased gas pressures of krypton and xenon.

5) Effects of simmer mode of operation.

6) Effects of simmer mode with a three electrode lamp.

4.1 Use of Fluorescent Envelope Materials for Increasing the Useful Light Output of Lamps

Xenon-filled lamps (4 mm bore x 2 inch arc length) with envelopes of fluorescent material and clear fused quartz were constructed during the first period. Cerium was incorporated in the quartz envelope material to produce the fluorescence. The comparative spectra from those lamps for the visible region are illustrated in Figure 2. The spectrum of the cerium-doped envelope lamp is higher in the region between 0.40 microns and 0.65 microns. The ultraviolet region of the spectrum for these lamps is shown in Figures 3 and 4, and it can be seen that the ultraviolet portion of the spectrum is eliminated below 0.3 microns for the cerium-doped envelope lamp.

The elimination of this portion of the spectrum can aid greatly in extending the life of coolants used in the laser systems as the organic coolants are degraded rapidly by the ultraviolet radiation. Other laser head components that should be similarly protected from ultraviolet radiation are the laser rod and the cavity reflecting surfaces. Titanium-doped envelopes are normally used for the suppression of the ultraviolet region of the spectrum, and a spectrum from such a lamp is shown in Figure 5. Radiation below 0.22 microns is absorbed.

The cerium-doped envelope suppresses much more of the ultraviolet than the titanium-doped envelope.

The cerium-doped envelope lamps were compared with the clear fused quartz envelope lamps (CFQ) for their useful light output to determine if the fluorescence can increase the pumping efficiency for Nd:YAG. For this purpose a standard 4L2 lamp (4 mm bore diameter, 2 inch arc length, 450 Torr xenon, CFQ envelope) was compared with a similar lamp with a cerium-doped envelope. At 10 joules input energy the useful light output was 1326 for the clear fused quartz and 1219 for the cerium doped quartz.

The useful light output for the cerium-doped quartz envelope lamp is 8% lower than that of the conventional lamp. This is surprising in that the cerium-doped envelope lamp has a higher output in the visible region and would be expected to increase the pumping of Nd:YAG by pumping the band at 0.58 microns. The samples of YAG that are used for the useful light output measurements are lutetium-doped Nd:YAG, and this may allow the UV component of the light output to aid in the pumping of the Nd. Also the concentration of the cerium in the quartz may be too great and it may absorb in useful pump bands at 0.7 to 0.9 microns. The cerium-doped envelopes appear promising because of the decreased ultraviolet radiation and will be further investigated.

4.2 Use of Fluorescent Dyes to Increase Pumping Efficiency

The use of fluorescent dyes to increase the amount of light in the pump bands has been considered before[3, 4, 5] for ruby lasers and has been re-suggested many times. With the advent of dye lasers and the renewed investigation of long life dyes, it was considered a possibility that dyes might be available which would increase the pumping efficiency and would have lifetimes that are suitable for use in lasers or laser cavities with low duty cycles.

Many dyes were investigated. The one that was selected for pumping Nd:YAG was Rhodamine 6G (R6G). The R6G absorbs radiation between 0.4 and 0.5 microns and fluoresces between 0.53 and 0.68 microns. There is a pump band for Nd:YAG centered near the 0.58 micron region. These various regions are shown in Figure 6.

For testing the efficiency of the use of the fluorescent dye, a double cylinder cavity was constructed that would fit into the fluorescence analysis instrument. The lamp to be tested fits into the dye cylinder. All light from the lamp passes through the cylinder prior to entering the detector unit in the fluorescence analysis instrument. The ultraviolet portion of the light causes fluorescence of the dye. Background readings were taken with the cylinder filled with methanol, the solvent for the dye. The dye cell is shown in Figure 7.

Three lamps were used: a 4 mm bore, 2 inch arc length lamp, filled with 450 Torr of xenon, a comparable lamp with a cerium-doped envelope, and a 3 mm bore lamp filled with 1500 Torr of xenon. It was anticipated that the increased fluorescence of the cerium-doped envelope might provide increased pumping by converting the UV light from the lamp into the pump band of the fluorescent dye.

The variation of useful light output with concentration of the dye is shown in Figure 8. It can be seen that the concentration is not critical over a broad range. The useful light outputs for three lamps are shown in Figure 9. The fluorescent dye does improve the useful light output by 15% in the CFQ lamp. However, the life of the dye is not long, and after approximately 50 shots at the 10 joule level the useful light output is reduced to the background level, i.e., the level achieved with only methanol in the dye cell. The degradation with pulsing is shown is Figure 10.

The conclusion is reached that the use of fluorescent dyes will increase the laser output; however, the lifetime of the dyes is the limiting factor at present.

4.3 Effects of Smaller Bore Diameters

The effect of different bore diameters was measured by fabricating lamps of 4, 3, 2.5 and 2 mm bore and 2.125 inch arc length. The lamps were tested for their useful light output with external triggering at a pulse energy of 7.5 joules, and the results are shown in Figures 11 and 12, for lamps filled with xenon and krypton. The smaller bore diameters increase the useful light output for bore diameters down to 2.5 mm. There does not seem to be much further increase in the useful light output by using a 2 mm bore diameter lamp in place of a 2.5 mm bore diameter.

In prior work the bore diameter variation was found to be more critical in the actual laser application than in the fluorescence analysis instrument, since the diameter of the lamp influences the imaging of the arc in the laser rod. All of these lamps will be tested in a laser cavity for the final determination of improvement. As the bore diameter is decreased the life of the lamps will decrease, and a satisfactory trade off will need to be established between bore diameter and life.

4.4 Effect of Increased Gas Pressures of Xenon and Krypton

The effect of increased gas pressures was determined by measuring the useful light output of lamps with 450, 1500, 3000, and 4500 Torr of the gases. Prior work indicated that as the pressure was increased up to 3000 Torr, the light output was also increased. This work was undertaken in order to determine if the effect continued with increased pressure.

The FOV versus pressure curves are shown in Figures 13 and 14, for 3 mm bore krypton and 4 mm bore xenon lamps with external triggering at a pulse energy of 7.5 joules. The data show that the useful light output increases with pressure. If external triggering is used, 1500 Torr is usually the practical limit for pressure, since difficulty in triggering the lamp increases with increased pressure. However, if the simmer mode of operation is used the lamp needs to be triggered only initially and it may be possible to use higher pressure lamps with their increased efficiency. These data show that efficiency will be increased 19% by using a 4500 Torr, lamp in place of the 1500 Torr krypton lamp, at 100μs pulse duration.

4.5 Effects of Simmer Mode of Operation

The simmer mode of operation has been shown in a prior program to increase the efficiency of operation of the lamp. During simmer operation the lamp is operated with a parallel dc circuit in addition to the pulse circuit. The simmer circuit is shown in Figure 15.

Increases in efficiency of laser operation -- without including the simmer power in the total power -- are about .0% to 25%. However, 15% to 20% extra energy is presently dissipated in the simmer circuit although only 2% to 5% of that energy is dissipated in the lamp itself, the balance being dissipated in a ballast resistor.

The details of the simmer mode were investigated in order to reduce the simmer power needed. The voltage-current curve for a simmer circuit is shown in Figure 16 for a 3 mm bore x 2.5 inch arc length lamp filled with 1500 Torr of krypton. For 4.8 watts into the lamp, the voltage drop across the lamp is 240 volts and the current is 20 mA. For a lamp operating at 10 joules per pulse and at 20 pps the PFN power is 200 watts, and the useful light output and laser output may be increased by 20% with the use of 2.4% extra power in the lamp simmer. However, an additional 2.9 watts is dissipated in the resistor in series with the lamp.

The increase in useful light output for various powers in the lamp simmer is illustrated in Figure 17. The current through the lamp may be decreased to 5 mA while not appreciably reducing the effect of the simmer mode of operation. At these low values of simmer current, difficulty exists in maintaining the simmer operation as the arc is sometimes "blown out" by the main pulse. At the 10 to 20 mA current level the arc is relatively stable. Comparisons of light output for a normally operated lamp with external trigger and the same lamp with various values of simmer current are shown in Figure 18 and Table III.

4.6 Simmer Mode Operation of a Three-Electrode Lamp

The increased efficiency resulting from the simmer mode of operation can be explained as resulting from the presence of easily-ionized metastable atoms produced by vacuum ultraviolet radiation from the simmer discharge, or alternatively as being due merely to the heating and preionizing action of the simmer discharge. In order to obtain information that might assist in choosing between these explanations, the lamp illustrated in Figure 19 was constructed. It had a 3 mm bore and a 2.125 inch arc length and was filled with 1500 Torr of krypton. A small "coaxial gap" was formed between the

TABLE III

USEFUL LIGHT OUTPUT VALUES FOR EXTERNAL TRIGGER
AND SIMMER OPERATION
(10 JOULES, 100μs PULSE)

Simmer Current (mA)	0	5	10	20	70	100
Total Simmer Power (W)	0	3.5	8.4	7.7	20.9	33
Total Simmer Voltage (V)	0	695	840	384	299	330
Ballast Resistance Kohms	-	43	43	7.2	1.7	1.7
Lamp Simmer Power (W)	0	2.4	4.1	4.8	12.6	16
Lamp Simmer Voltage (V)	0	480	410	240	180	160
Useful Light Output (Relative)	1520	1760	1762	1788	1815	1815
Useful Light Comparison to External Trigger Operation %	100	115	116	117.3	119	119

Preferred
Operating
Conditions

tungsten anode and the insulated tungsten rod inside the tubular anode. An arc across this coaxial gap could be maintained with a voltage drop of only 108 V using a series ballast resistor of 43 Kohms and an open circuit voltage of 1000 V across the gap and series ballast. The gap was also operated with a power supply that used an active ballast, which did not require a series resistor, and had an efficiency of 80% in expending electrical energy in the gap. The gap was intended to furnish a source of electrons, ions, metastables, and ultraviolet radiation at lower voltage and power than the conventional simmer discharge running the whole length of the lamp.

Useful light output measurements were made with gap simmer currents of 6.7 and 20 mA. For comparison, measurements were also made with the gap shorted out and the lamp operating as a two-electrode lamp with external series triggering, and with a conventional simmer discharge running the whole length of the lamp. The results of these measurements, listed in Table IV, show the conventional simmer operation with a current of 70 mA and a power dissipation (in the lamp) of 15.6 W results in a 29% increase in useful light output as compared with operation with no simmer current. The coaxial simmer with a current of 20 mA and a power dissipation (in the lamp) of only 2.16 W results in an increase of 24% in useful light output. The data in Table III indicate that in conventional simmer operation, reducing the simmer power from 15.6 W to 2.16 W would reduce the useful light output by about 5%. Therefore, a conventional simmer of 2.16 W in the three-electrode lamp (with the gap shorted out) would give about 24% more useful light output than operation without the simmer discharge, or about the same improvement as is given by the coaxial simmer at 2.16 W.

The fact that the coaxial simmer discharge at one end of the lamp is at least as effective as a conventional simmer discharge with the same power dissipation, running the whole length of the lamp, indicates that the beneficial effect of the simmer discharge is an "action at a distance" and is probably the result of vacuum ultraviolet resonance radiation emitted by the simmer discharge. This radiation produces resonance-excited

TABLE IV

USEFUL LIGHT OUTPUT VALUES FOR THREE ELECTRODE LAMP

(3 MM, 2.125 INCH, 1500 TORR KRYPTON, 10 JOULES, 100μ s)

	Externally Triggered Lamp	Full Simmer		Coaxial Gap Simmer	
Simmer Current (mA)	0	3.6*	70	6.7	20
Lamp Simmer Power (W)	-	2.16*	15.6	.72	2.16
Simmer Voltage (V)	-	600*	214	108	108
Useful Light Output (Relative)	1318	1625*	1693	1540	1630
Useful Light Output Comparison to External Trigger Operation	100%	124*	129	117	124

*Extrapolated Values

atoms throughout the gas volume, and some of these atoms are converted in gas collisions into metastable atoms of long lifetime. These metastable atoms have an ionization potential of only 4 eV, as compared to 14 eV for ground-state krypton atoms. Their presence makes it possible for the main discharge to expand more rapidly, with lower values of electron temperature and current density during the expansion phase of the discharge, and the lower value of electron temperature results in a larger fraction of the input energy being converted into near-infrared line radiation that is useful in pumping the laser material.

Another possible effect of vacuum ultraviolet radiation is the production of photoelectrically generated electrons from the surfaces of the electrodes and the envelope.

In addition to being equally as efficient as the conventional simmer discharge, the coaxial simmer can be maintained at lower currents during pulsing, without "blowing out", than the full simmer. The coaxial gap simmer will also allow a simpler, separate power supply to be constructed with an active ballast eliminating the series resistor. The coaxial gap simmer mode requires normal external triggering in order to start the main pulse in the lamp.

5.0 REPRODUCIBILITY

The objective of this portion of the program is to determine the reproducibility of light output from a single lamp and the reproducibility of light output from lamp to lamp. The useful light output is measured on a fluorescence analysis tester that has been digitized. The readings on a single lamp are reproducible to +1/2% and the tester appears to have very little electrical drift, less than 1% in 6 months. The inside reflective coating deteriorates with time, 10% in a year, so standard lamps are used for calibration during each measurement. The device is illustrated schematically in Figure 20 and shown in Figure 21. Readings and deviations on a single lamp are taken for normal external trigger operation and for simmer operation.

5.1 Lamp to Lamp Variation

The First Triannaul Report contained an analysis that showed that the primary variation from lamp to lamp would be caused by a variation in the diameter of the tubing. Consequently four approaches to controlling the bore diameter were considered. The initial approach was to purchase tubing to tighter specifications. However, seven tubing manufacturers "no bid" the RFQ with tighter tolerances. Another approach was to select tubing that was within a range of 4 mm $\pm$0.05 mm, and a batch of 28 lamps was fabricated from the selected tubing. A third approach that was considered was the purchase of precision ground tubing. However, the cost of this approach ruled it out for standard lamps. A fourth approach was to shrink the quartz tubing onto a precision ground tungsten mandrel. This latter approach appears to be the most practical and economical method. A batch of 12 lamps was constructed with wall material of clear fused quartz that was shrunk onto precision ground tungsten mandrels. Tubing diameters were maintained within $\pm$0.001 inch, .006 mm.

Both batches of lamps had a 4 mm bore, were precision filled with 1500 Torr of xenon, and were fabricated and processed in the standard manner. Each lamp was operated for 10 pulses and the useful light output values recorded. Typical data for a single lamp are shown in Table V. The mean value for each lamp was calculated and the average deviation of the mean value for each lamp from the batch mean was also calculated. The lamps are quite reproducible within a batch. This indicates that the bore diameter and xenon fill pressure controls are adequate to fabricate lamps to meet the required $\pm$5% initial light output requirements. The simmer mode of operation is more reproducible than the externally triggered modes. Data for a batch of 9 lamps with envelopes of selected tubing is shown in Table VI.

The data for the two batches of lamps made with selected and shrunk down tubing are listed in Table VII. Lamps with "shrunk down envelopes" have a smaller average deviation and are more reproducible than lamps with "selected tubing".

TABLE V

USEFUL LIGHT OUTPUT FOR LAMP OPERATED IN NORMAL AND SIMMER MODE

(LAMP 1197. 4 MM BORE DIAMETER, 2.125 INCH ARC LENGTH, 1500 TORR XENON. PULSE ENERGY, 10 JOULES: SIMMER POWER, 7 WATTS)

	Normal	Simmer
	1555	1975
	1564	1975
	1570	1971
	1574	1978
	1574	1979
	1578	1975
	1588	1979
	1580	1979
	1578	1974
	1581	1982
Mean	1574.2	1977.0
Average Deviation	6.7	2.7
% Deviation of Mean	0.42%	0.13%

TABLE VI

USEFUL LIGHT VALUES
MEANS FOR NINE LAMPS WITH SELECTED QUARTZ ENVELOPES

(L-1197, 4 MM BORE X 2.125 INCH ARC LENGTH, 1500 TORR XENON)

Mean FOV*	Max.*	Min.*	Average Deviation*	Average Deviation, Percent*
1601.6	1623	1595	6.7	.41
1582.0	1611	1579	8.3	.52
1593.3	1605	1583	5.6	.35
1599.7	1607	1587	4.6	.28
1611.1	1619	1604	3.5	.21
1575.8	1580	1572	2.4	.15
1566.2	1572	1561	3.1	.19
1574.2	1588	1556	6.7	.42
1567.7	1575	1560	4.6	.29

*From 10 Shots on each lamp

	Value	%
Mean of Means for 9 lamps	1585.8	100
Maximum Single-Lamp Mean	1611.1	101.6
Minimum	1566.2	98.8
Range	44.9	2.83%
Average Deviation of Single-Lamp Means From Overall Mean	13.9	.87

TABLE VII

AVERAGE DEVIATION OF SINGLE LAMP MEANS
FROM MEAN FOR BATCH, PERCENT
(L1197 Lamps, Zero Hours Life, Series Triggered)

Batch	Number of Lamps in Batch	Avg. Dev. of Single Lamp Means	Range
Selected Tubing $\pm1.25\%$ in i.d.	28	1.17%	2.7%
Shrunk-down Tubing $\pm0.63\%$ in i.d.	12	0.78%	2.9%

5.2 Life Tests

The objective of this portion of the program is to produce a lamp that will maintain a nearly constant light output over 10 million pulses. The specific laser test requirement is that the laser output decrease by not more than 10% in 1 million pulses. Final tests will be carried out in a laser to establish the correlation between the decrease in laser output and the decrease in light output.

An initial batch of 28 lamps was constructed from selected tubing and used for the life test. These lamps were constructed as follows:

Designation	L1197, Selected
Bore Diameter	4 mm ±0.05 mm (selected)
Arc Length	2.125 Inch
Fill Gas	Xenon
Pressure	1500 Torr
Wall Material	Clear Fused Quartz

These lamps were tested at 10 joules, 100μs pulse width, and 20 pps in the life test unit described in the First Tri-annual Report of this contract. The lamps were water cooled in a totally reflective cylindrical cavity, in which the reflected radiation is more intense than in a laser cavity.

Ten of these lamps were life tested and the data are shown in Figure 22. It can be seen that a 15% decrease in useful light output occured in the first million pulses and the useful light output stayed comparatively constant over the next nine million pulses. One of these lamps was further tested to 50 million pulses and showed no further degradation.

By heating one of these aged lamps with a torch two thirds of the 15% degradation was reversed. This 10 % increase in useful light output is due to color centers formed in the quartz that re-combine upon heating. Most of the initial light decrease could be prevented if the color center formation could be inhibited. The color center formation has been well described in the liter-ature, and is primarily due to the reactions of the impurities aluminum and lithium in the quartz. The concentration range of impurities in commercially available quartz is given in Table VIII. Aluminum is the primary impurity in naturally occuring quartz. Synthetic quartz is chemically refined prior to fabrication to pro-duce chemically pure SiO_2, and the resulting quartz has very low impurity levels.

A type of high purity synthetic quartz, "Suprasil", was used as an envelope material to construct two lamps. They should be expected to maintain high useful light output values during life testing. The useful light output during life is shown in Figure 22 and is nearly constant, with only a 4% fall off during the life testing. The 4% fall off confirms the fact that two thirds of the 15% degradation in the initial batch of lamps was due to color center formation, as there are no impurities in the "Suprasil" to form color centers. "Suprasil" is not a practical material for lamps that require organic coolants because it transmits U.V. radiation, which decomposes organic coolants, and may degrade laser materials.

The optimal lamp at the present state of knowledge appears to be one with a pure quartz envelope that is doped with an ultraviolet absorbing material.

TABLE VIII

IMPURITIES IN CLEAR FUSED QUARTZ (PARTS PER MILLION)

Al	47.6-220.0
Fe	2.0-4.1
Ti	1.0-2.3
Ca	1.4-5.0
Mg	1.2-2.0
K	<1.0-1.6
Na	<1.0-2.2
Li	1.8-10.0
B	2.0-4.0
Zr	<1.0
Total	63.7-246.0

6.0 PRELIMINARY MEASUREMENTS ON PUMP LAMPS FOR HOLMIUM LASERS

Preliminary measurements were performed to determine the most suitable lamp filling gases and operating parameters for pumping Ho:YLF (holmium-doped $LiYF_4$). The laser wavelength of this material is at 2.07 microns, which makes it relatively safe with regard to the possibility of producing retinal damage.

The absorption spectrum of a sample of Ho:YLF between 0.2 and 1.8 microns was measured and is shown in Figure 23. A large proportion of the absorption throughout this region represents useful laser pumping regions where light is absorbed either by holmium ions or by ions of other rare-earth dopants that can transfer their energy to the holmium. The occurrence of significant absorption in the region between 0.2 and 0.6 microns is important because the continuum emission of a xenon flashtube peaks at 0.3 microns (see Figure 3). In addition, there is considerable overlap between the strong xenon line emission at 0.83 microns and the absorption band centered at 0.8 microns.

The decay time constant of the fluorescence from a sample of Ho:YLF was measured with a pulsed xenon lamp and was found to be 10.6 ms.

In order to make useful light output comparisons on lamps for pumping Ho:YLF lasers, the fluorescence analysis instrument was modified by incorporating crystals of the doped and undoped laser material, the appropriate filters, and lead selenide detectors. The effect of pulse duration was determined using a 4 mm bore, 450 Torr xenon lamp. The results of these measurements, which are presented in Table IX and Figure 24, indicate that the pulse length is not very critical, and that a pulse length between 200 and 800 μs is optimum. Further measurements to determine the effects of other parameters were therefore made at pulse durations between 200 and 250 μs.

Xenon flashlamps with bore diameters of 3, 4, and 5 mm were operated in the fluorescence analysis instrument. The 3 mm bore lamp was found to be most efficient in producing useful light output.

The effect of different filling pressures was investigated using 5 mm bore xenon lamps filled to 450 and 3000 Torr. The 3000 Torr lamp was more efficient by 14%.

Xenon flashlamps were operated with normal external triggering and also in the simmer mode. The simmer operation gave an increase of as much as 24% in useful light output as compared with external triggering, at 200 -250μs, and 15% at 460μs.

Measurements were also made on alkali vapor lamps, operated in the simmer-pulse mode, over a range of vapor pressures. For potassium-rubidium lamps, it was found that the useful light output passes through a maximum at a pressure corresponding to a simmer voltage gradient of about 30 V/cm, and decreases as the pressure is increased beyond this point. The spectrum of a pulsed potassium-rubidium lamp operating near the optimal vapor pressure is shown in Figure 25. For comparison, the spectrum of a 1500 Torr xenon flashlamp is shown in Figure 26. Figure 27 shows a typical oscilloscope trace of the current and voltage for a pulsed potassium-rubidium lamp, together with the fluorescent output voltage from a Ho:YLF crystal excited by the lamp.

Results of all the measurements are given Table X and summarized in bar-chart form in Figure 28. It is apparent from these data that xenon lamps are superior to pulsed alkali vapor lamps for pumping Ho:YLF lasers, and that the efficiency of xenon lamps for this purpose increases with increasing pressure and decreasing bore diameter, and is higher for simmer than for series-triggered operation.

TABLE IX

FLUORESCENT OUTPUT VOLTAGE OF Ho:YLF SAMPLE WITH VARIOUS LAMPS

SIMMER AT 15J

LAMP	BORE	FILL	PRESSURE	DURATION	F.O.V.	SIMMER VOLTAGE
L730	4 mm	Xenon	450	0.22 ms	640 mV	-
L730	4 mm	Xenon	450	0.45 ms	600 mV	-
184	5 mm	K-Rb	-	0.27 ms	190 mV	87
184	5 mm	K-Rb	-	0.28 ms	280 mV	103
184	5 mm	K-Rb	-	0.27 ms	300 mV	115
62	6.3 mm	K-Rb	-	0.25 ms	300 mV	105
62	6.3 mm	K-Rb	-	0.27 ms	340 mV	145
62	6.3 mm	K-Rb	-	0.25 ms	330 mV	170
62	6.3 mm	K-Rb	-	0.25 ms	250 mV	220
66	6.3 mm	Rb	-	0.25 ms	200 mV	65
106	6.3 mm	Na	-	0.26 ms	160 mV	88

SERIES TRIGGERING AT 15J

LAMP	BORE	FILL	PRESSURE	DURATION	F.O.V.	SIMMER VOLTAGE
L730	4 mm	Xenon	450	0.25 ms	515 mV	-
730	4 mm	Xenon	450	0.46 ms	520 mV	-
730	4 mm	Xenon	450	0.12 ms	505 mV	-
730	4 mm	Xenon	450	0.68 ms	480 mV	-
905-001	3 mm	Xenon	450	0.25 ms	520 mV	-
907-001	5 mm	Xenon	450	0.28 ms	480 mV	-
907-003	5 mm	Xenon	3000	0.27 ms	550 mV	-

7.0 REFERENCES

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2. N. L. Yeamans and J. E. Creedon, "Long-Life-High-Repetition-Rate Flash Tubes", R&D Technical Report ECOM-3043, Nov. 1968.

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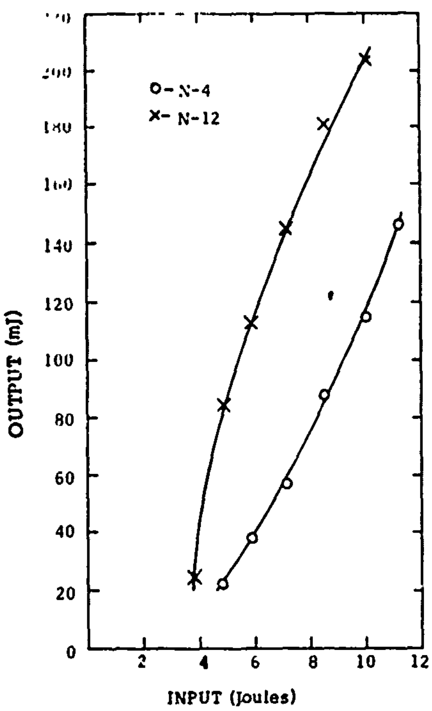
4. H. R. Koenig, "Ruby and Neodymium Laser Excitation Techniques", GE Research and Development Center Rpt. No. 66-C-116 (Oct. 1966).

5. W. W. Wladimiroff, "Some Stable Fluorescent Converter Solutions Enhancing Optical Pumping in the Visible Region", Photochem. and Photobio. 6, 543 (1967).



LASER DATA

Rod:	Nd:YAG, 1/4" x 2-1/2"
A/R Coating:	None
Output Mirror:	55% Reflective
Cavity:	Elliptical, Close Wrapped
Coolant:	Water
Inductance:	9 Microhenries
Capacitance:	47.3 Microfarads (not critically damped, not optimized)
Operating Mode:	Normal
Pulse Repetition Rate:	10 pps.

LAMP DATA

	Lamp N-4	Lamp N-12
Lamp Bore Diameter (mm):	4	3
Lamp Arc Length (inches):	2.125	2.125
Lamp Fill Gas:	Xenon	Krypton
Lamp Fill Pressure (Torr):	450	3000
Initiation Method:	External	Simmer Pulse

FIGURE 1. LASER OUTPUT DATA FOR 3000 TORR KRYPTON LAMP AND 450 TORR XENON LAMP

1034

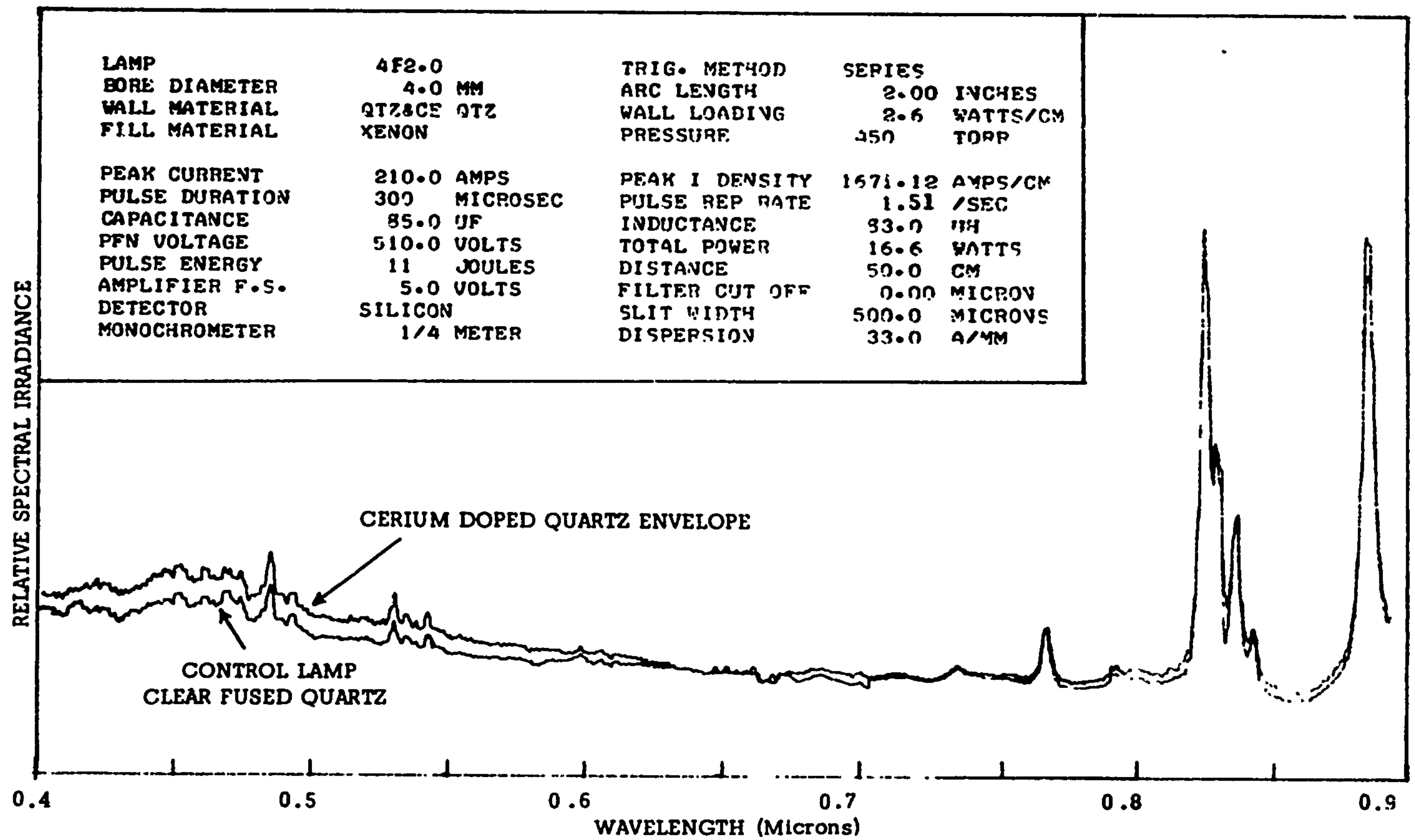


FIGURE 2 COMPARATIVE SPECTRAL DATA FOR A CERIUM DOPED QUARTZ ENVELOPE LAMP AND A STANDARD QUARTZ ENVELOPE LAMP

2099

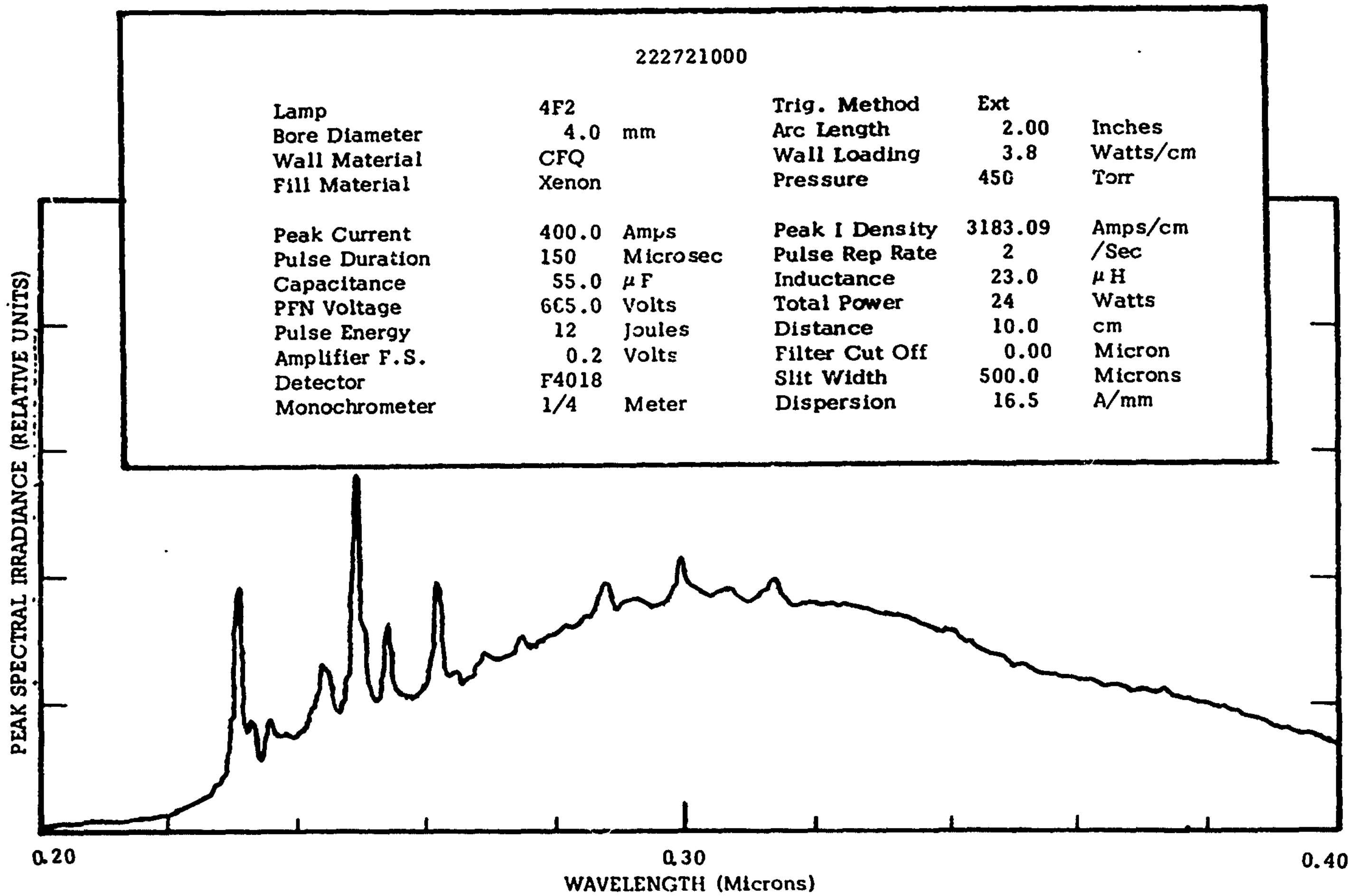
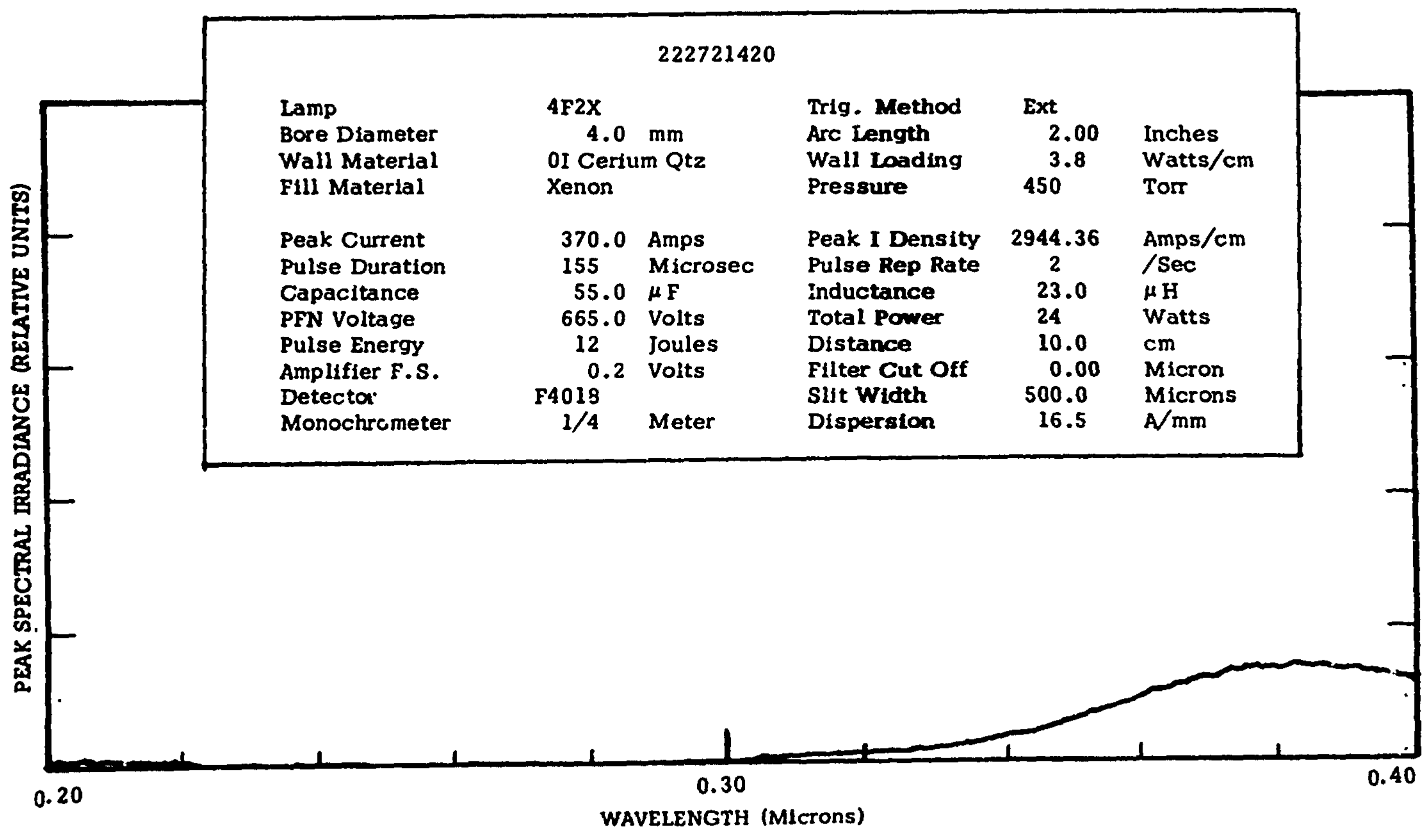


FIGURE 3. ULTRAVIOLET SPECTRUM OF XENON LAMP WITH CLEAR FUSED QUARTZ ENVELOPE

4380



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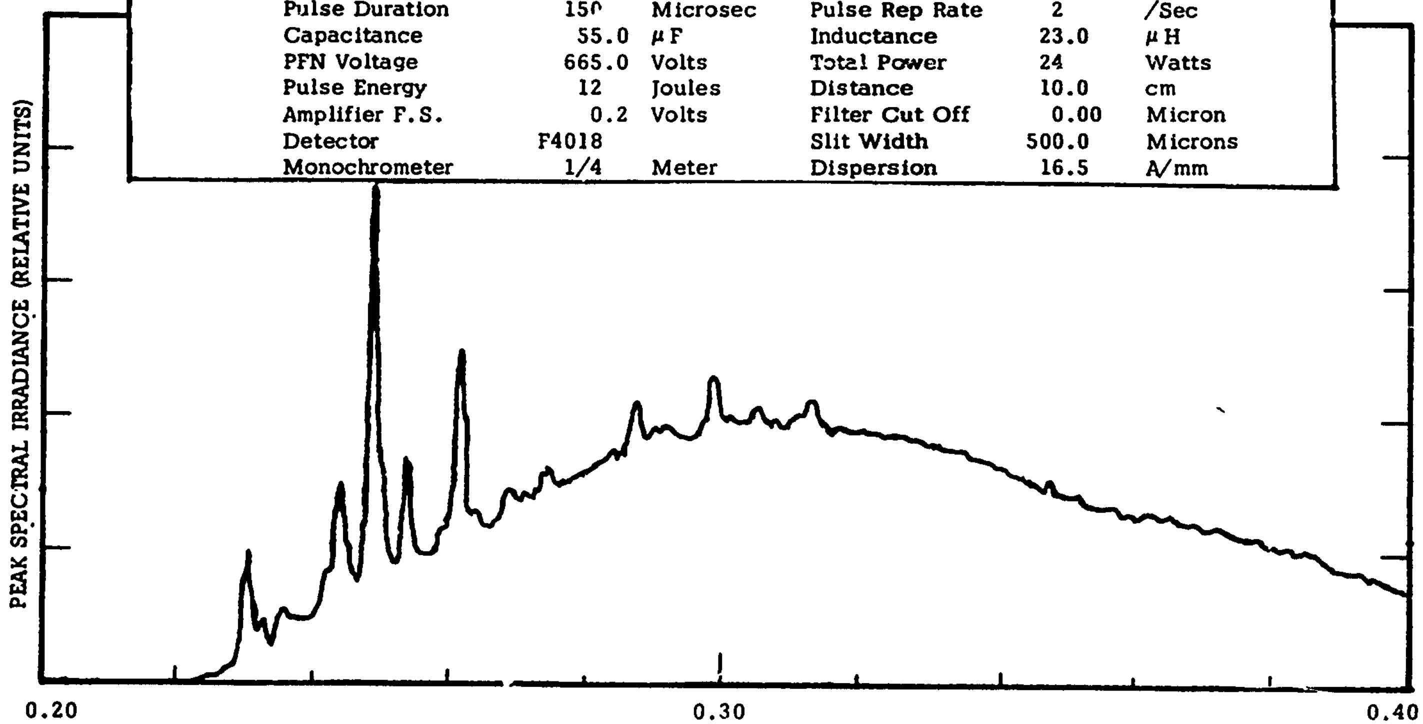
Lamp	4F2X		Trig. Method	Ext	
Bore Diameter	4.0	mm	Arc Length	2.00	Inches
Wall Material	01 Cerium Qtz		Wall Loading	3.8	Watts/cm
Fill Material	Xenon		Pressure	450	Torr
Peak Current	370.0	Amps	Peak I Density	2944.36	Amps/cm
Pulse Duration	155	Microsec	Pulse Rep Rate	2	/Sec
Capacitance	55.0	μF	Inductance	23.0	μH
PFN Voltage	665.0	Volts	Total Power	24	Watts
Pulse Energy	12	Joules	Distance	10.0	cm
Amplifier F.S.	0.2	Volts	Filter Cut Off	0.00	Micron
Detector	F4018		Slit Width	500.0	Microns
Monochrometer	1/4	Meter	Dispersion	16.5	A/mm

FIGURE 4. ULTRAVIOLET SPECTRUM OF XENON LAMP WITH CERIUM-DOPED QUARTZ ENVELOPE



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Lamp	L349.0		Trig. Method	Ext	
Bore Diameter	4.0	mm	Arc Length	2.12	Inches
Wall Material	Germisil		Wall Loading	3.6	Watts/cm
Fill Material	Xenon		Pressure	450	Torr
Peak Current	400.0	Amps	Peak I Density	3183.09	Amps/cm
Pulse Duration	150	Microsec	Pulse Rep Rate	2	/Sec
Capacitance	55.0	μF	Inductance	23.0	μH
PFN Voltage	665.0	Volts	Total Power	24	Watts
Pulse Energy	12	Joules	Distance	10.0	cm
Amplifier F.S.	0.2	Volts	Filter Cut Off	0.00	Micron
Detector	F4018		Slit Width	500.0	Microns
Monochrometer	1/4	Meter	Dispersion	16.5	A/mm

FIGURE 5. ULTRAVIOLET SPECTRUM OF XENON LAMP WITH TITANIUM-DOPED QUARTZ ENVELOPE

4382

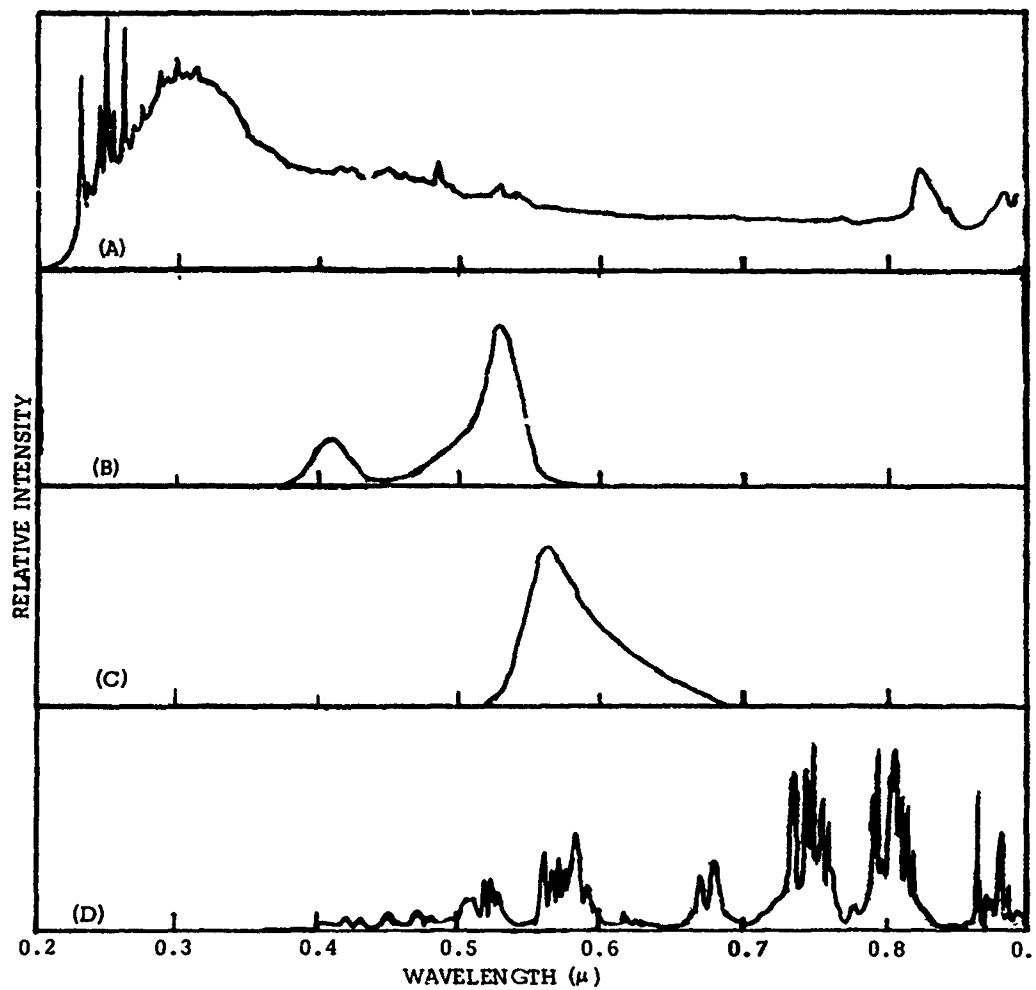


FIGURE 6 (A) SPECTRUM OF XENON LAMP, 0.2–0.9μ (B) ABSORPTION SPECTRUM OF R6G DYE (C) FLUORESCENCE SPECTRUM OF R6G DYE (D) EXCITATION SPECTRUM OF Nd:YAG

4383

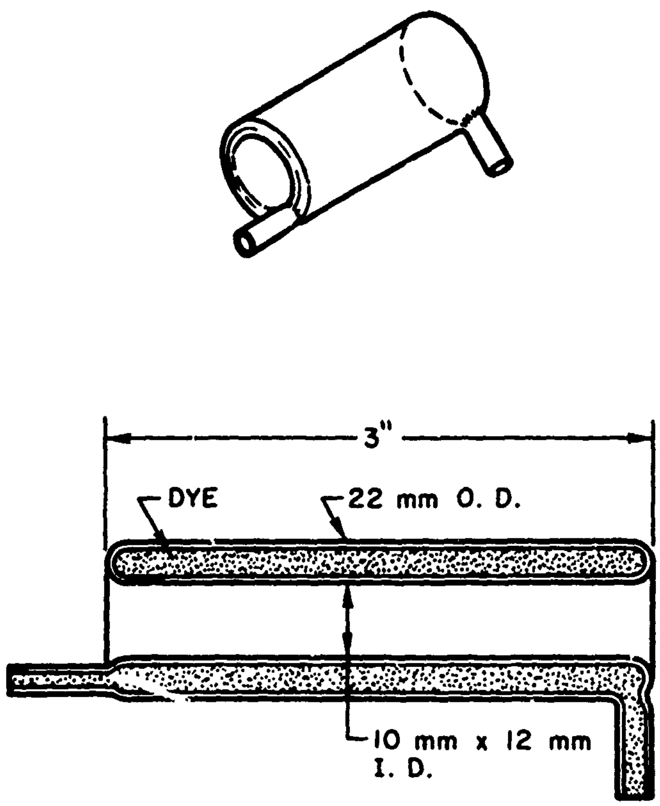


FIGURE 7 DYE CELL

43R'

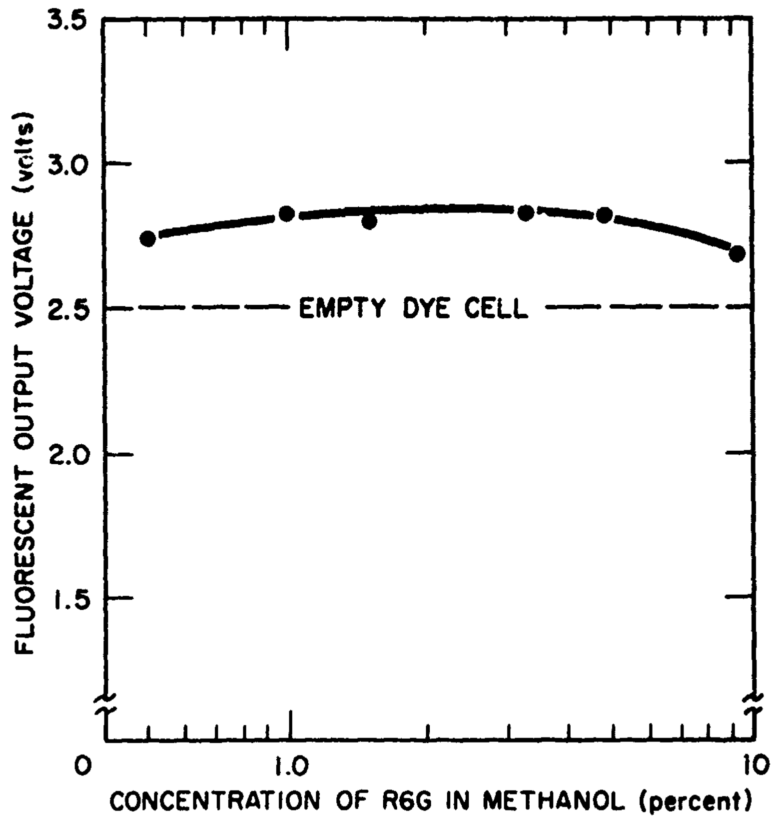


FIGURE 8 VARIATION OF INITIAL USEFUL LIGHT OUTPUT WITH DYE CONCENTRATION

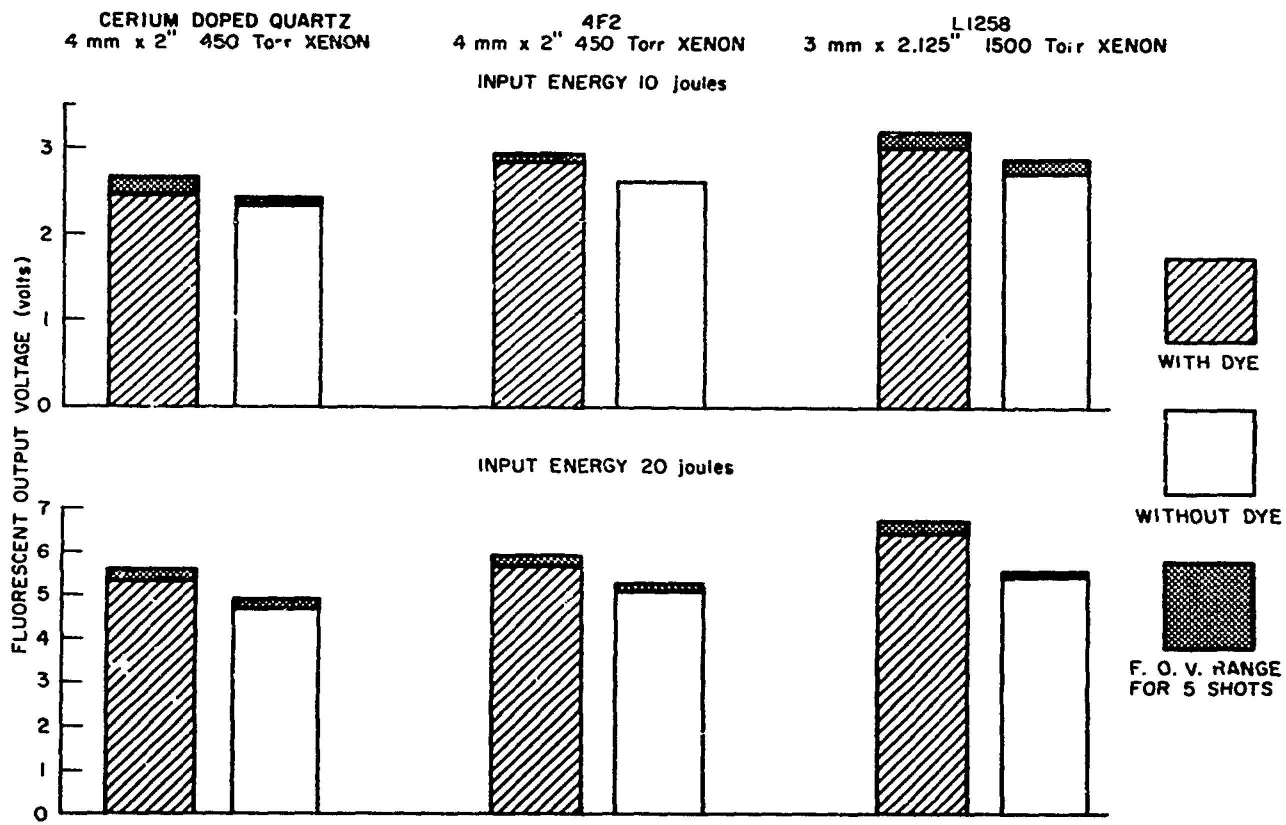


FIGURE 9 USEFUL LIGHT OUTPUT FOR VARIOUS LAMPS WITH AND WITHOUT R6G DYE CELL AT 10 AND 20 JOULES

4379

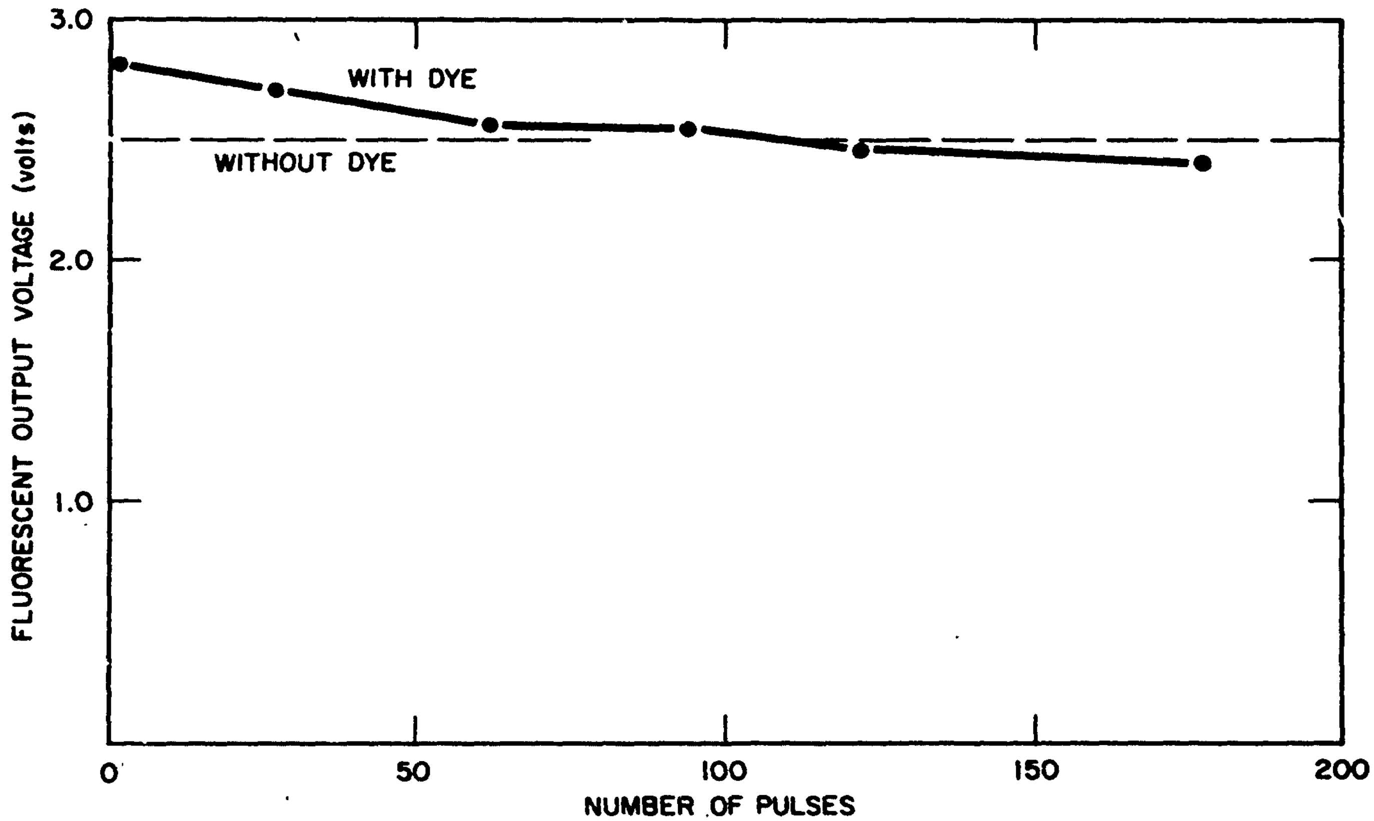


FIGURE 10 VARIATION OF USEFUL LIGHT OUTPUT FROM DYE CELL WITH NUMBER OF PULSES

4386

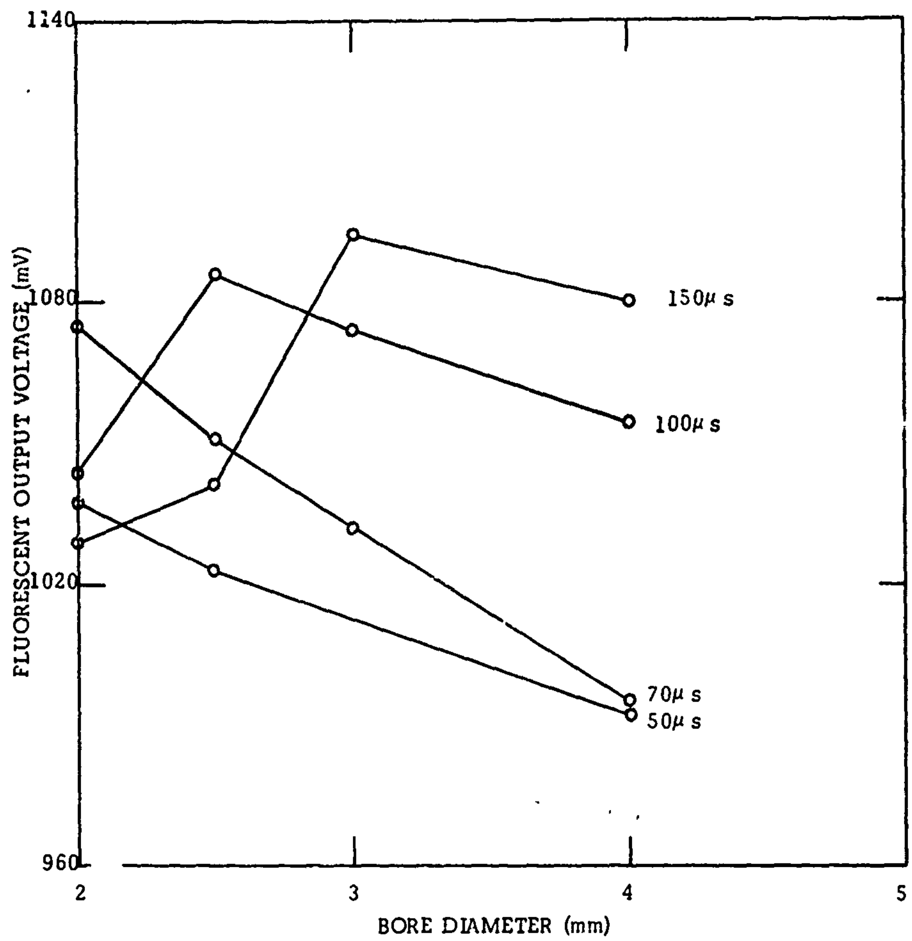


FIGURE 11. USEFUL LIGHT OUTPUT OF 1500 TORR XENON LAMPS AS A FUNCTION OF BORE DIAMETER AT VARIOUS PULSE DURATIONS

(ARC LENGTH 2.125 INCHES, PULSE ENERGY 7.5 JOULES, EXTERNAL TRIGGERING)

4387

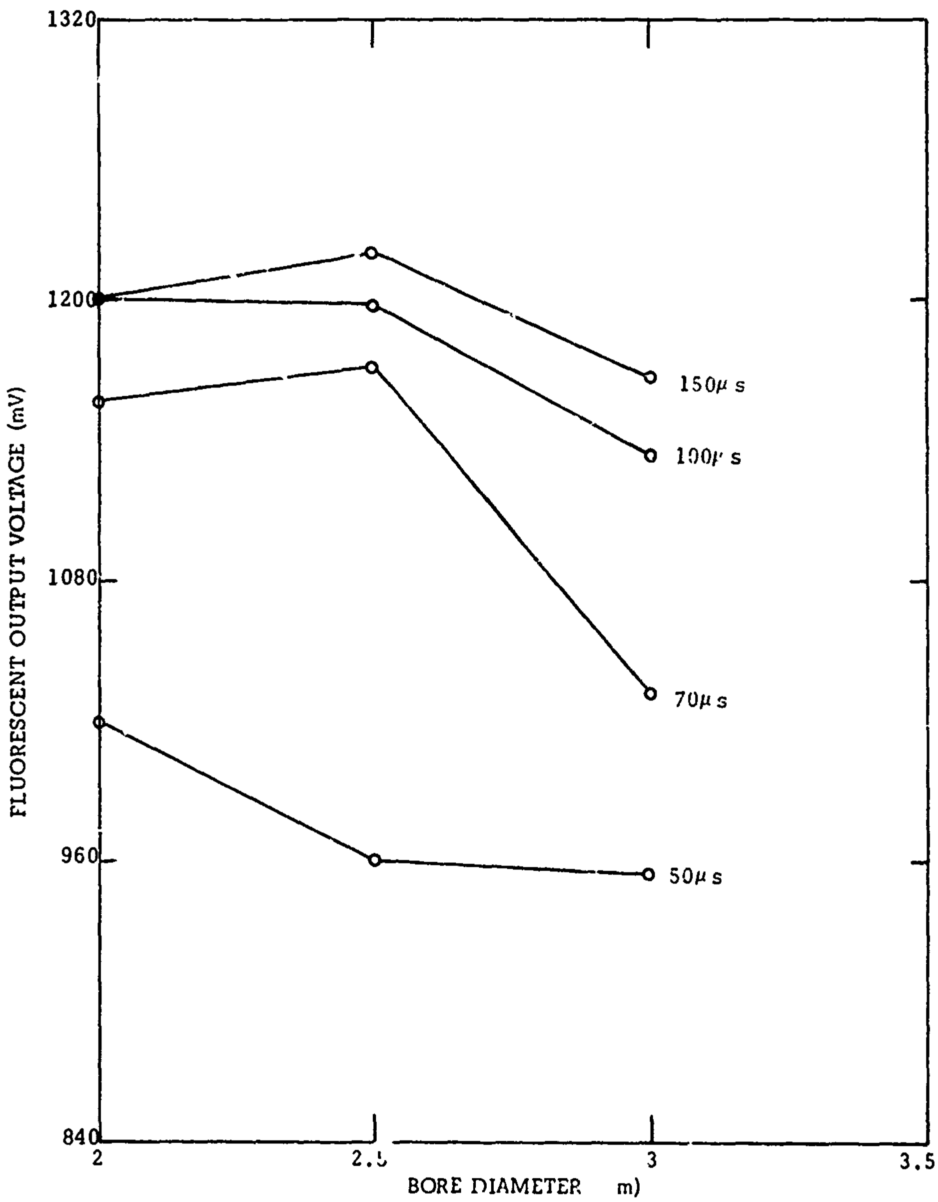


FIGURE 12. USEFUL LIGHT OUTPUT OF 3000 TORR KRYPTON LAMPS AS A FUNCTION OF BORE DIAMETER FOR VARIOUS PULSE DURATIONS (ARC LENGTH 2.125 INCHES, PULSE ENERGY 7.5 JOULES, EXTERNAL TRIGGERING)

4388

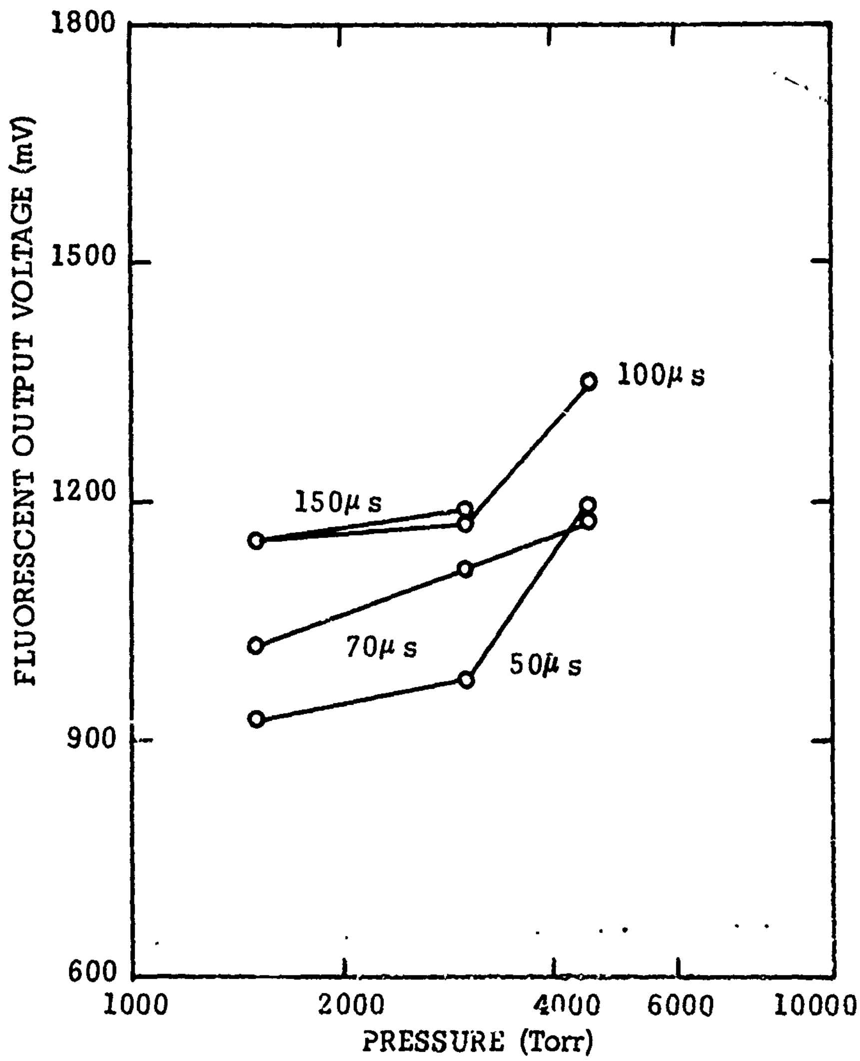


FIGURE 13. USEFUL LIGHT OUTPUT OF KRYPTON LAMPS AS A FUNCTION OF PRESSURE AT VARIOUS PULSE DURATIONS (ARC LENGTH 2.125 INCHES, BORE DIAMETER 3 MM, PULSE ENERGY 7.5 JOULES, EXTERNAL TRIGGERING)

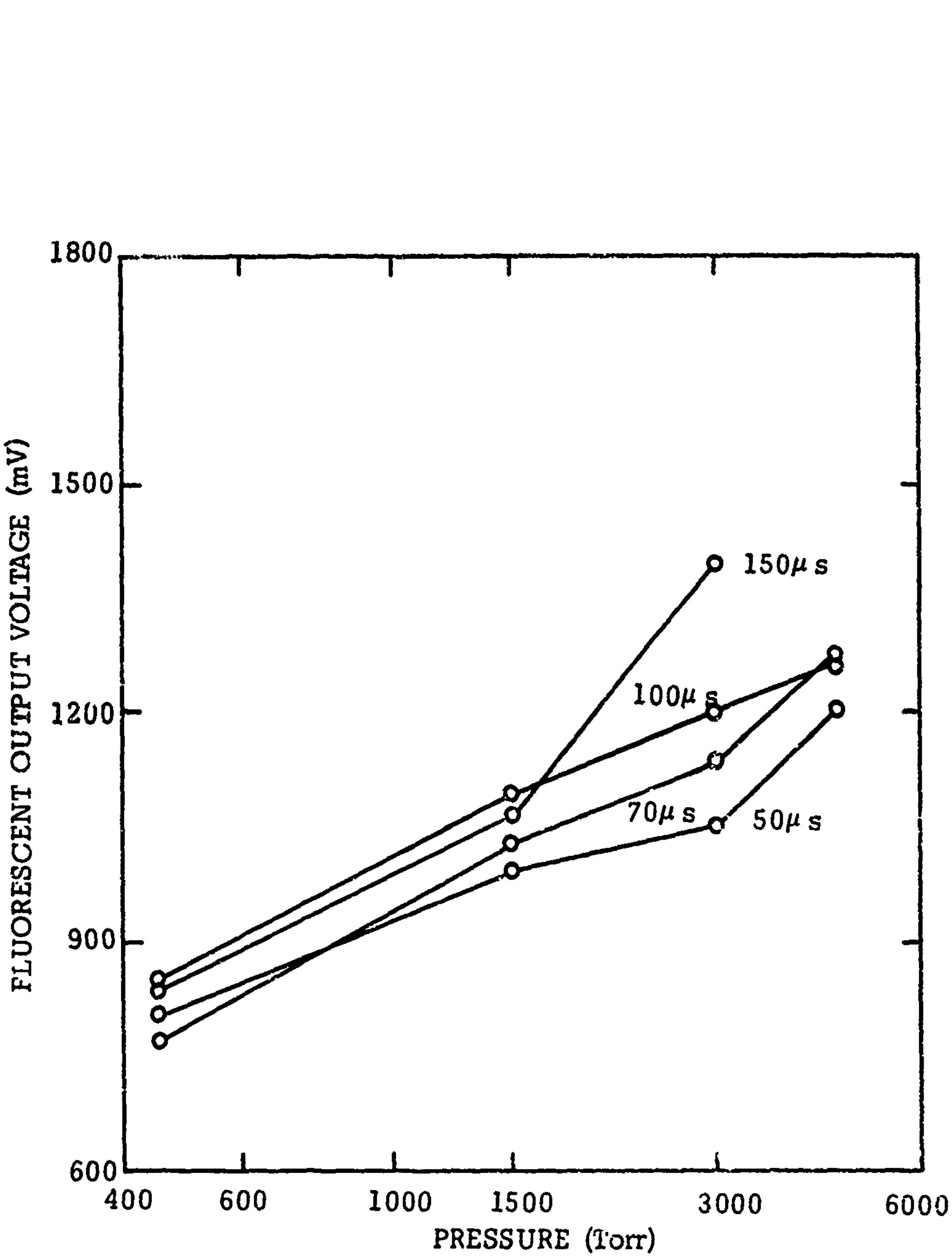


FIGURE 14. USEFUL LIGHT OUTPUT OF XENON LAMPS AS A FUNCTION OF PRESSURE AT VARIOUS PULSE DURATIONS (ARC LENGTH 2.125 INCHES, BORE DIAMETER 4 MM, PULSE ENERGY 7.5 JOULES, EXTERNAL TRIGGERING)

4390

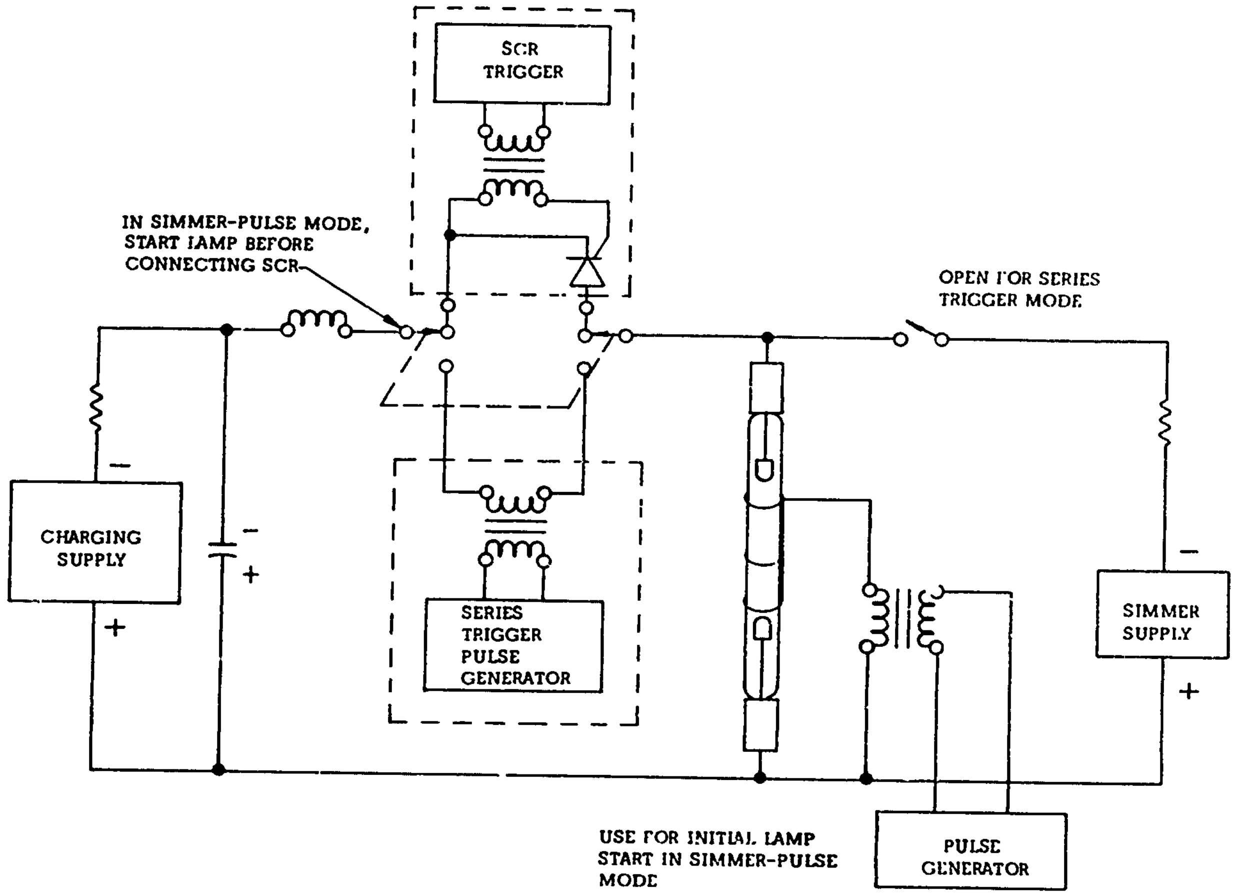


FIGURE 15. PULSE POWER SUPPLY WITH OPTIONAL SIMMER MODE

1006

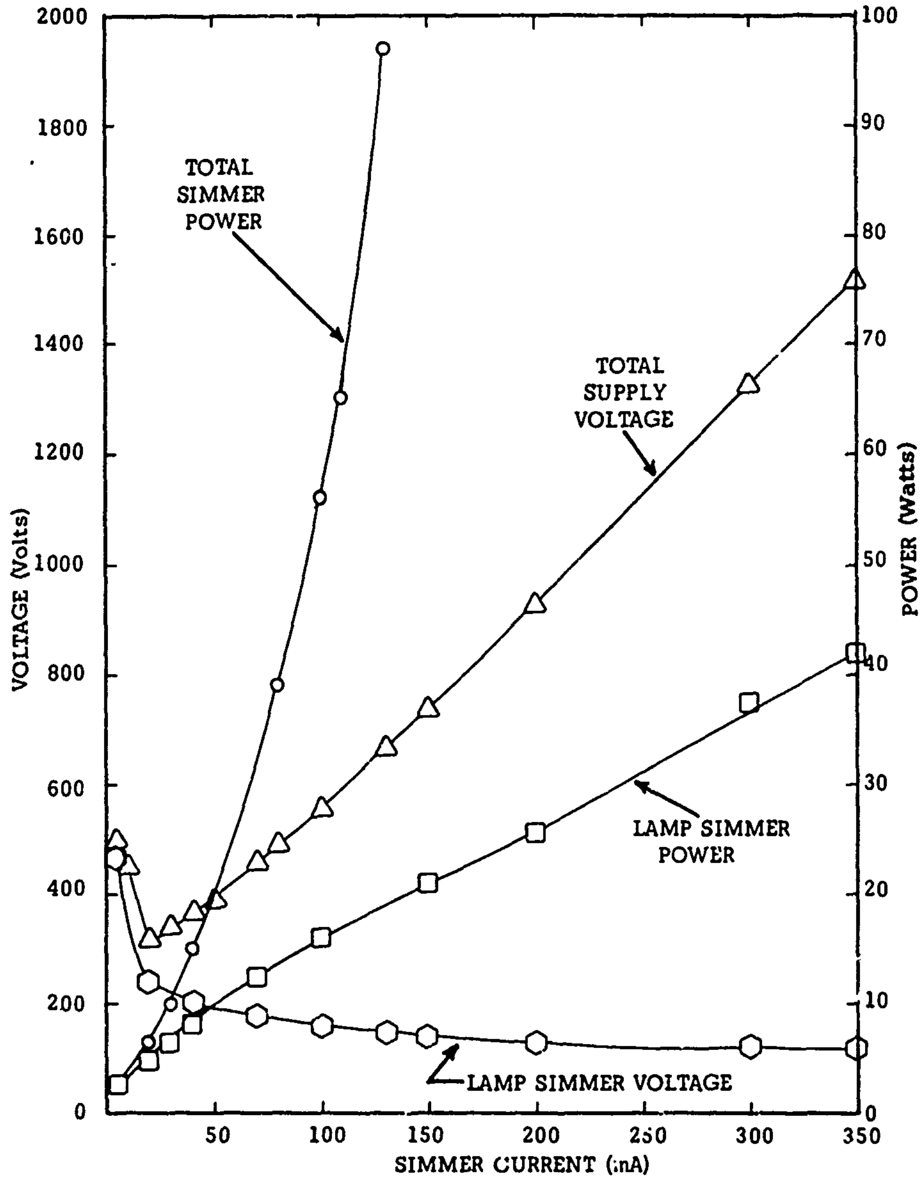


FIGURE 16. SIMMER VOLTAGE, CURRENT, AND POWER FOR A 3 MM X 2.5 INCH, 1500 TORR KRYPTON FLASHLAMP

4391

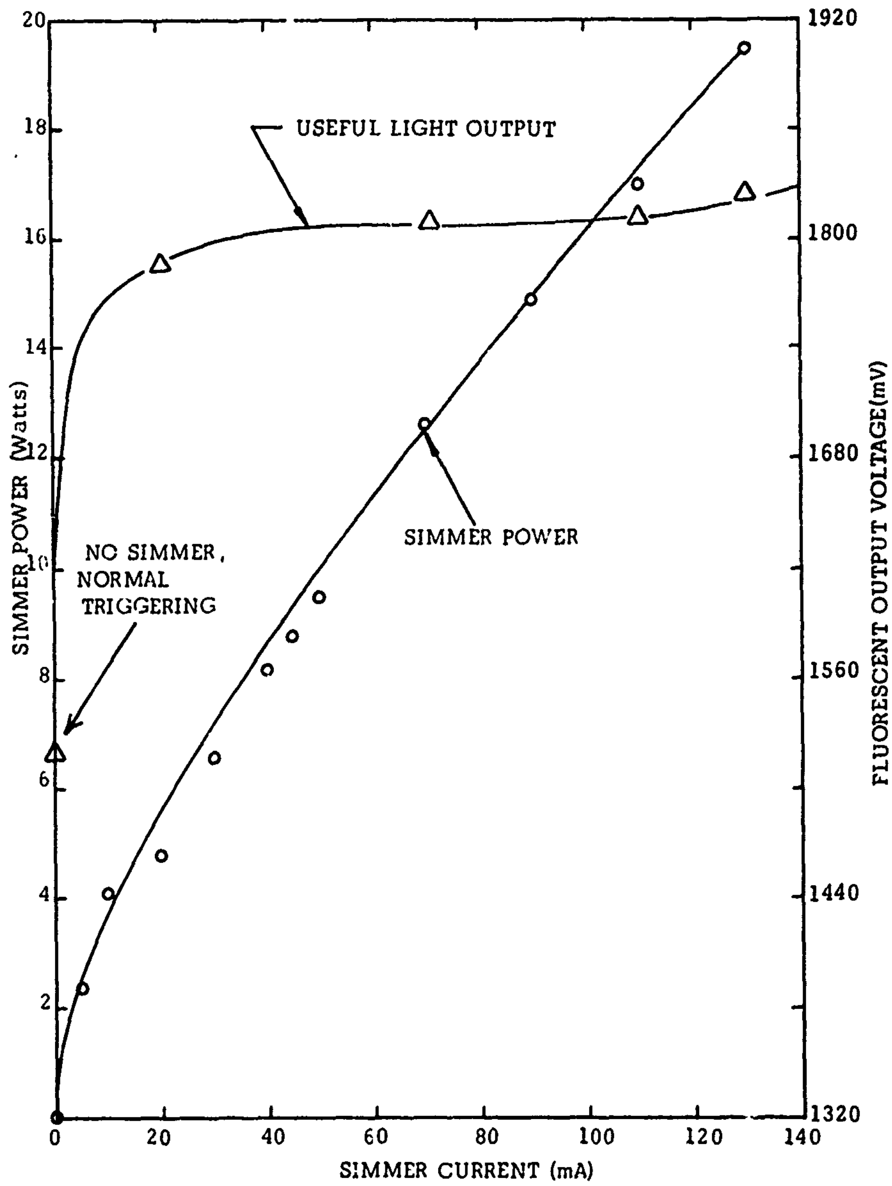


FIGURE 17. SIMMER POWER AND USEFUL LIGHT OUTPUT FOR A 3 MM X 2.5 INCH, 1500 TORR KRYPTON LAMP

4392

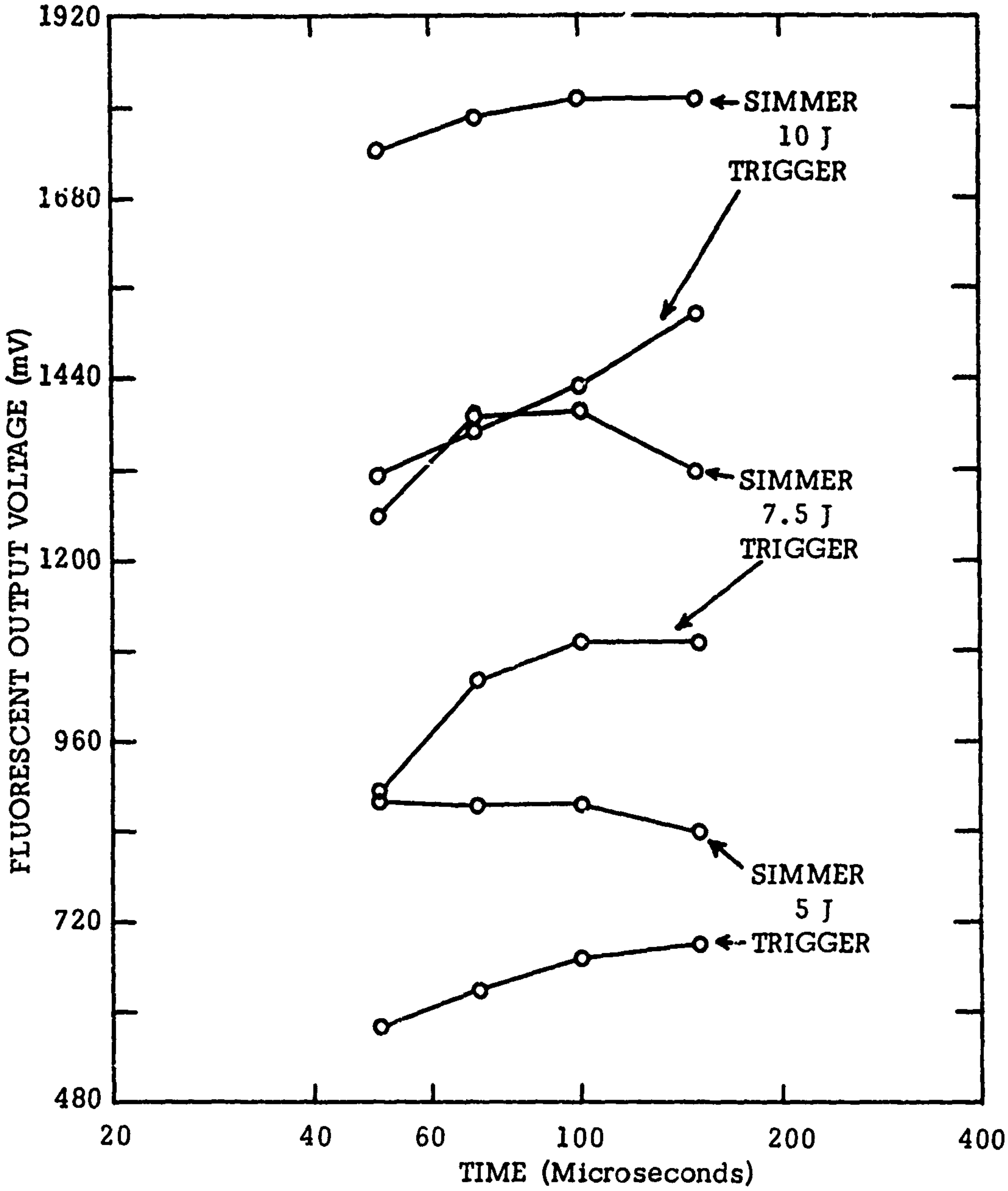


FIGURE 18. USEFUL LIGHT OUTPUT FOR 3 MM X 2.125 INCH, 1500 TORR KRYPTON LAMP

4377

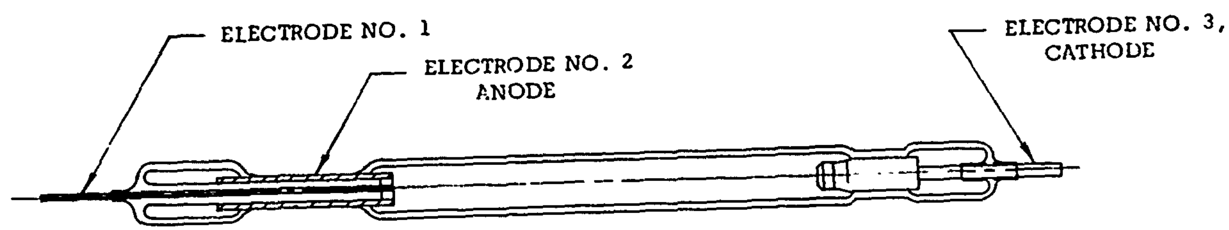


FIGURE 19. THREE-ELECTRODE LAMP

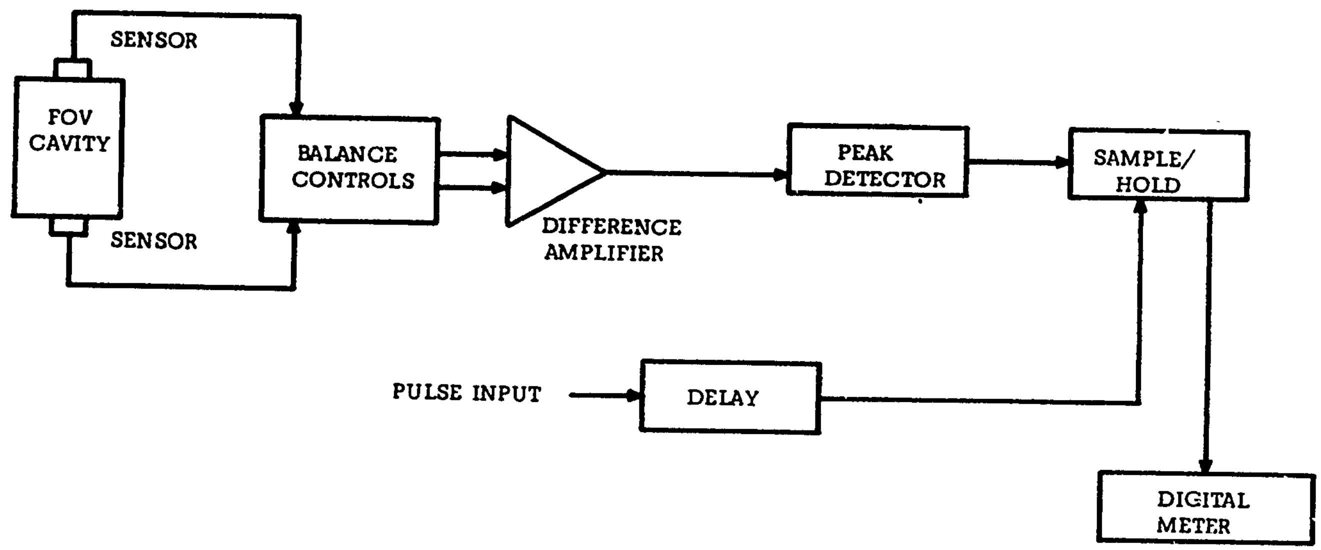


FIGURE 20. SCHEMATIC DIAGRAM OF PULSED FLUORESCENT ANALYSIS TESTER WITH DIGITAL READOUT ATTACHMENT

4009

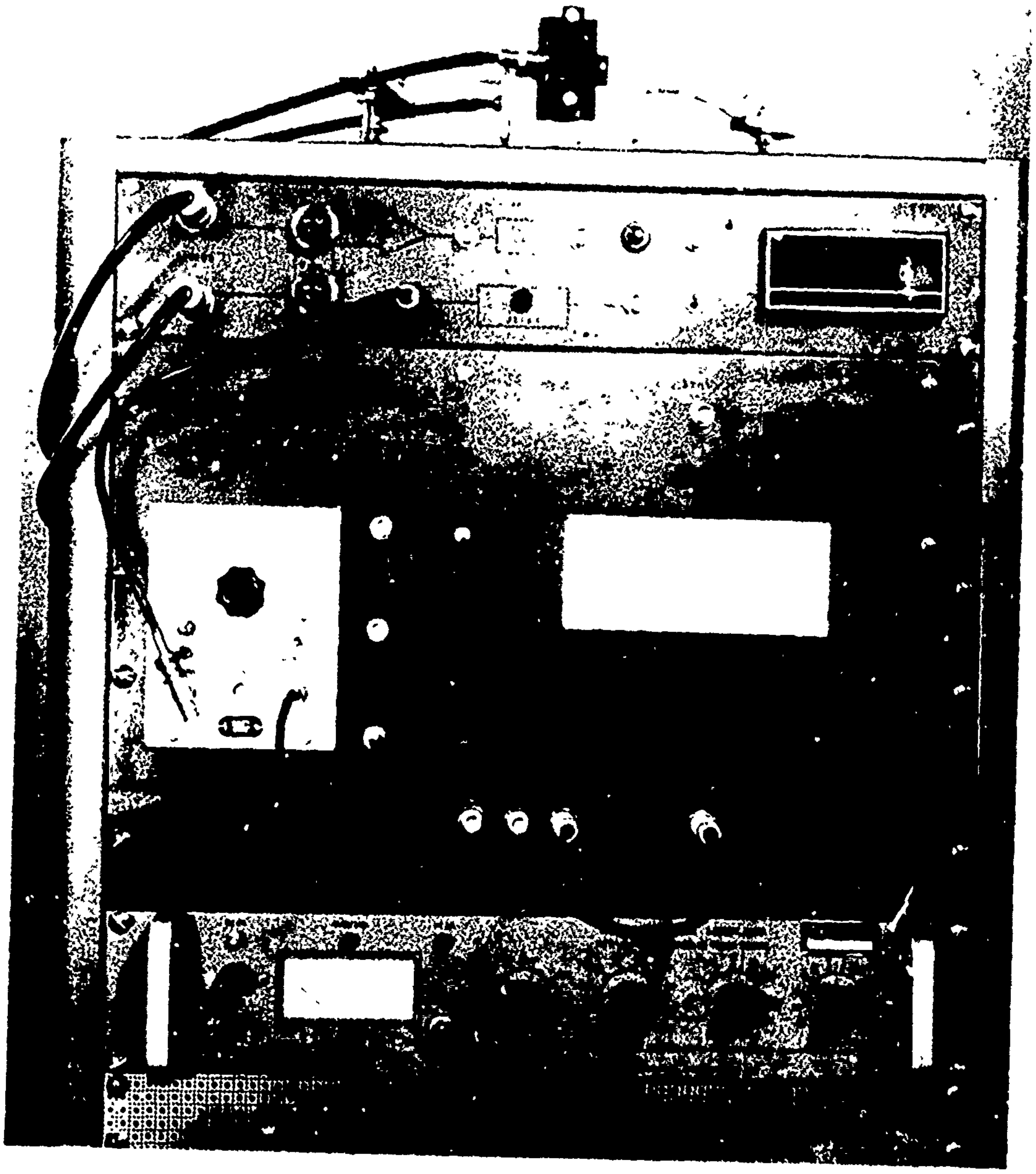


FIGURE 21. PHOTOGRAPH OF PULSED FLUORESCENT ANALYSIS TESTER WITH DIGITAL READOUT ATTACHMENT

4010

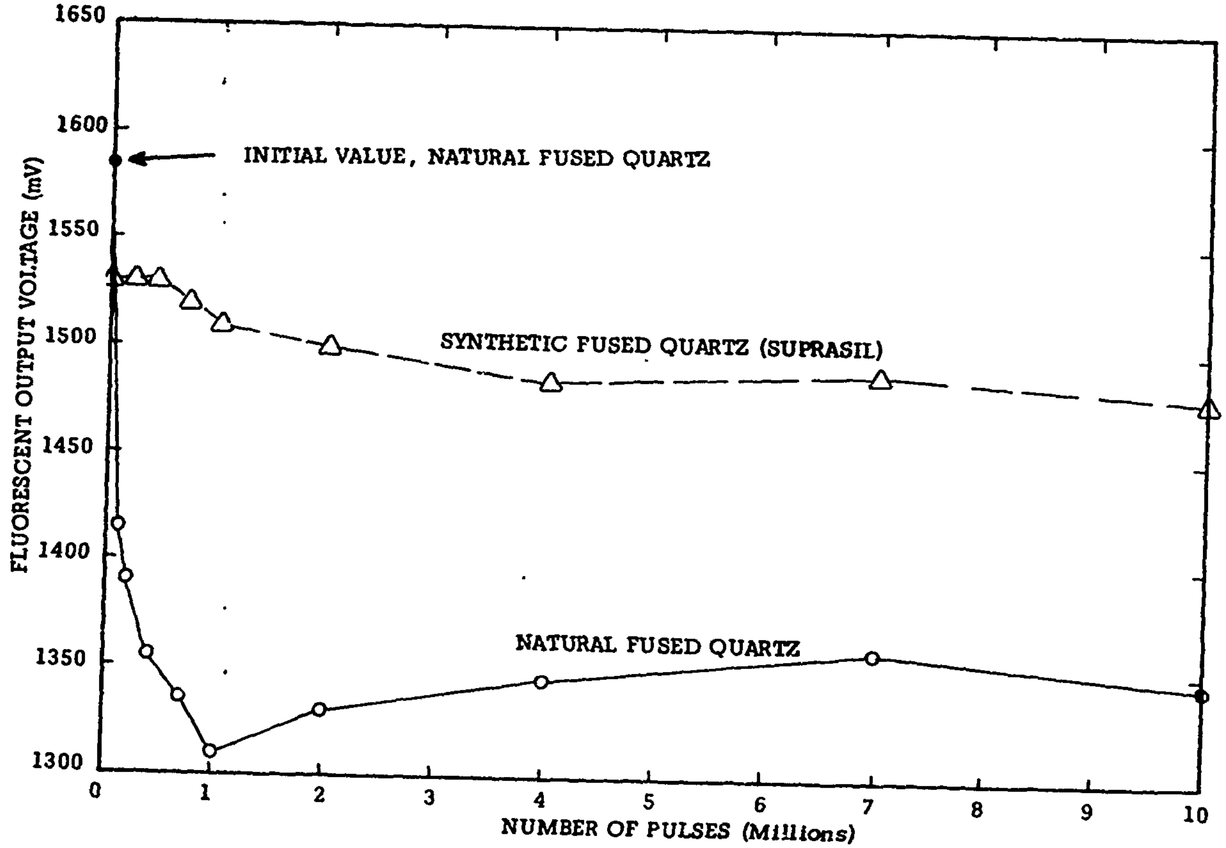


FIGURE 22. VARIATION OF USEFUL LIGHT OUTPUT WITH NUMBER OF PULSES FOR TWO ENVELOPE MATERIALS

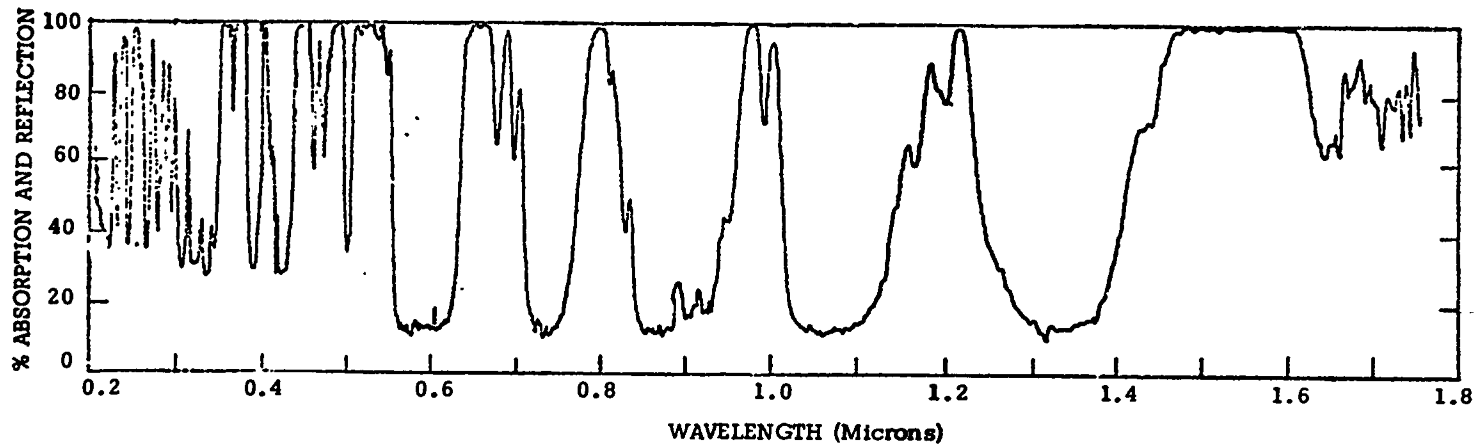


FIGURE 23. PERCENT ABSORPTION AND REFLECTION FOR 1/4 INCH THICK SAMPLE OF HO:YLF

4394

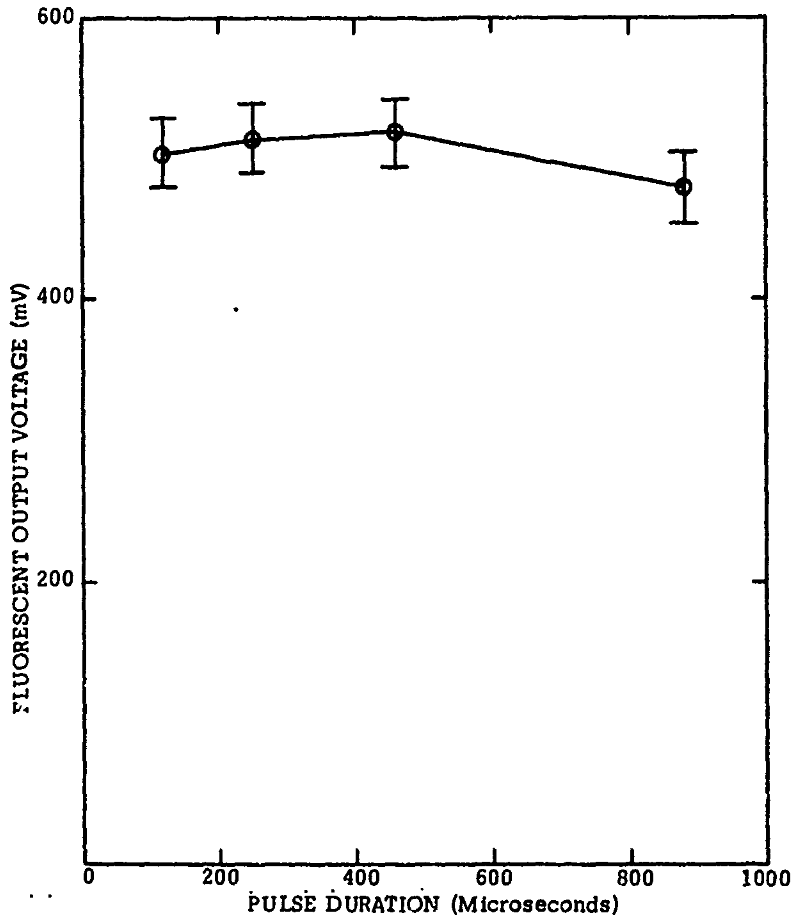


FIGURE 24. Ho:YLF FLUORESCENT OUTPUT VOLTAGE OF 4 MM X 2.125 INCH, 450 TORR XENON LAMP AS A FUNCTION OF PULSE DURATION WITH SERIES TRIGGERING

4395

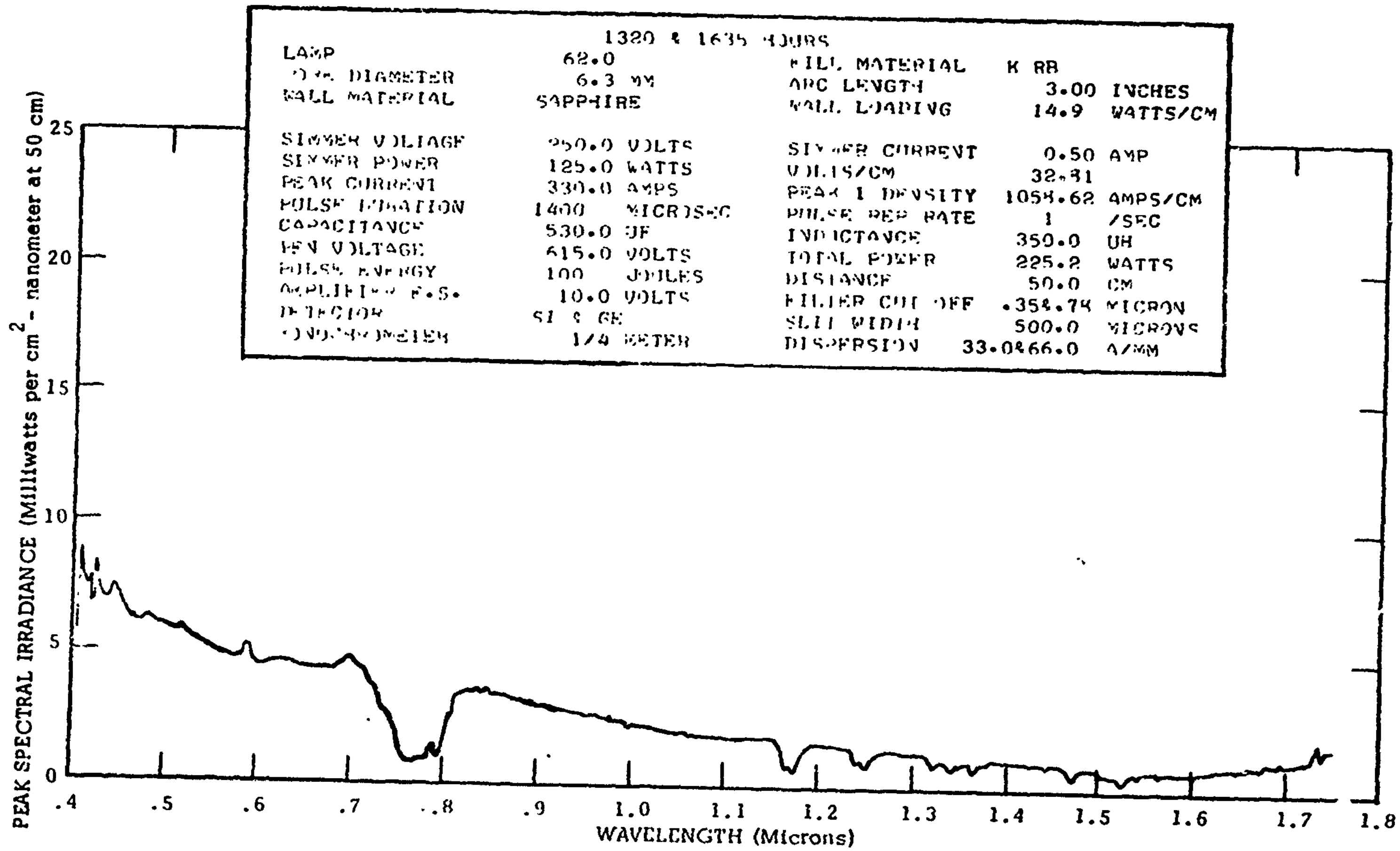


FIGURE 25. SPECTRUM OF PULSED POTASSIUM-RUBIDIUM LAMP AT PRESSURE CORRESPONDING TO 33 V/cm

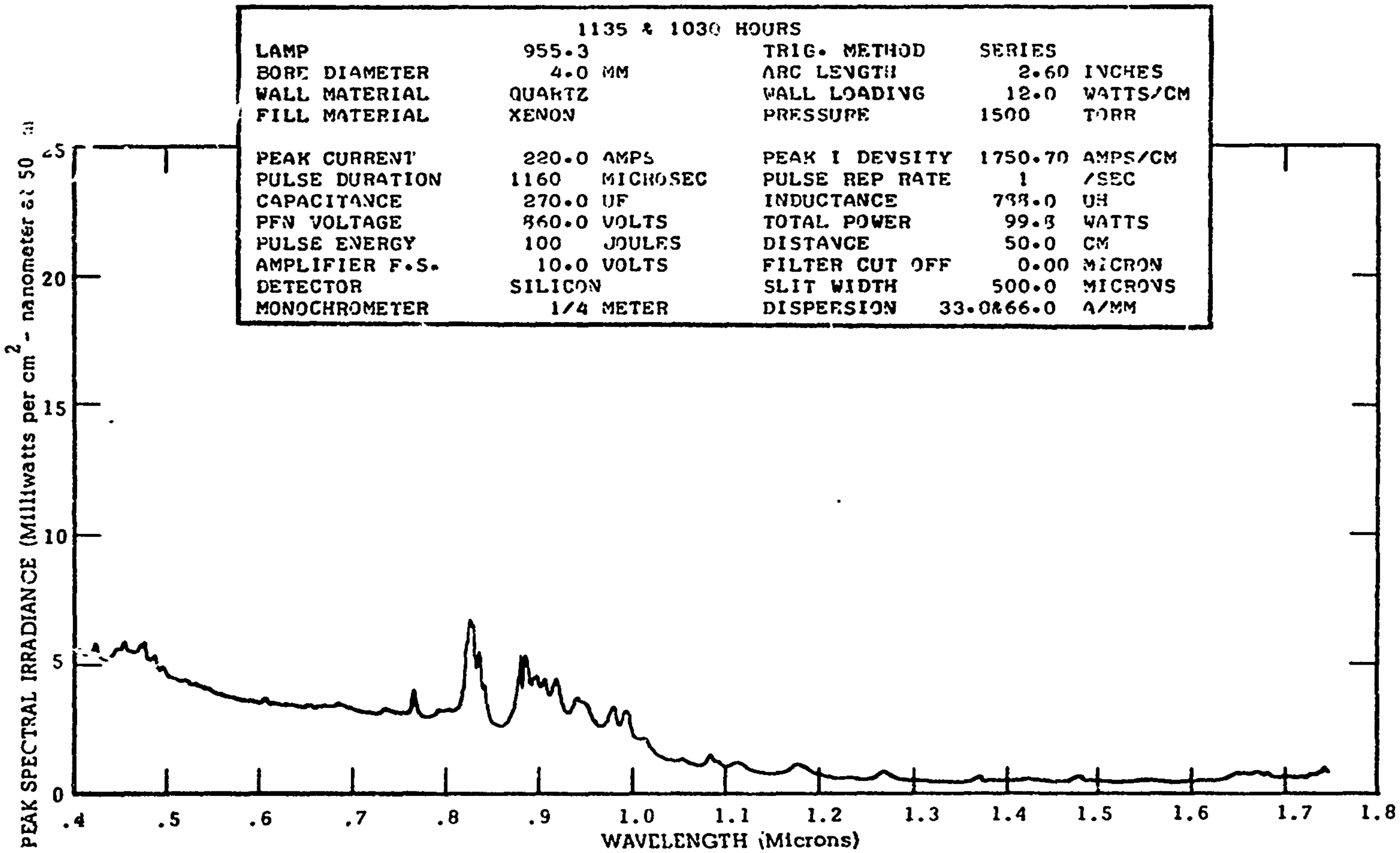
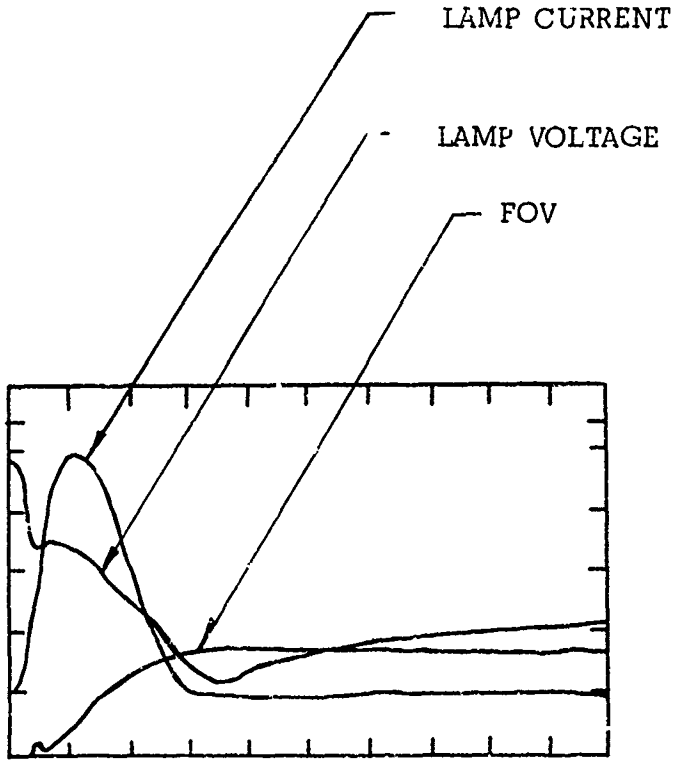


FIGURE 26. SPECTRUM OF 1500 TORR XENON FLASHLAMP AT A PEAK CURRENT DENSITY OF 1750 A/cm^2

47-21



Vertical Scale:	Voltage, 200 V/div. Current, 100 V/div. F.O.V., 200 mV/div.
Horizontal Scale:	100 μ s/div.
K-Rb Lamp,	Simmer at 30 V/cm 15 Joule Pulse

FIGURE 27. TYPICAL OSCILLOSCOPE TRACE OF LAMP PARAMETERS AND Ho:YLF FLUORESCENCE.

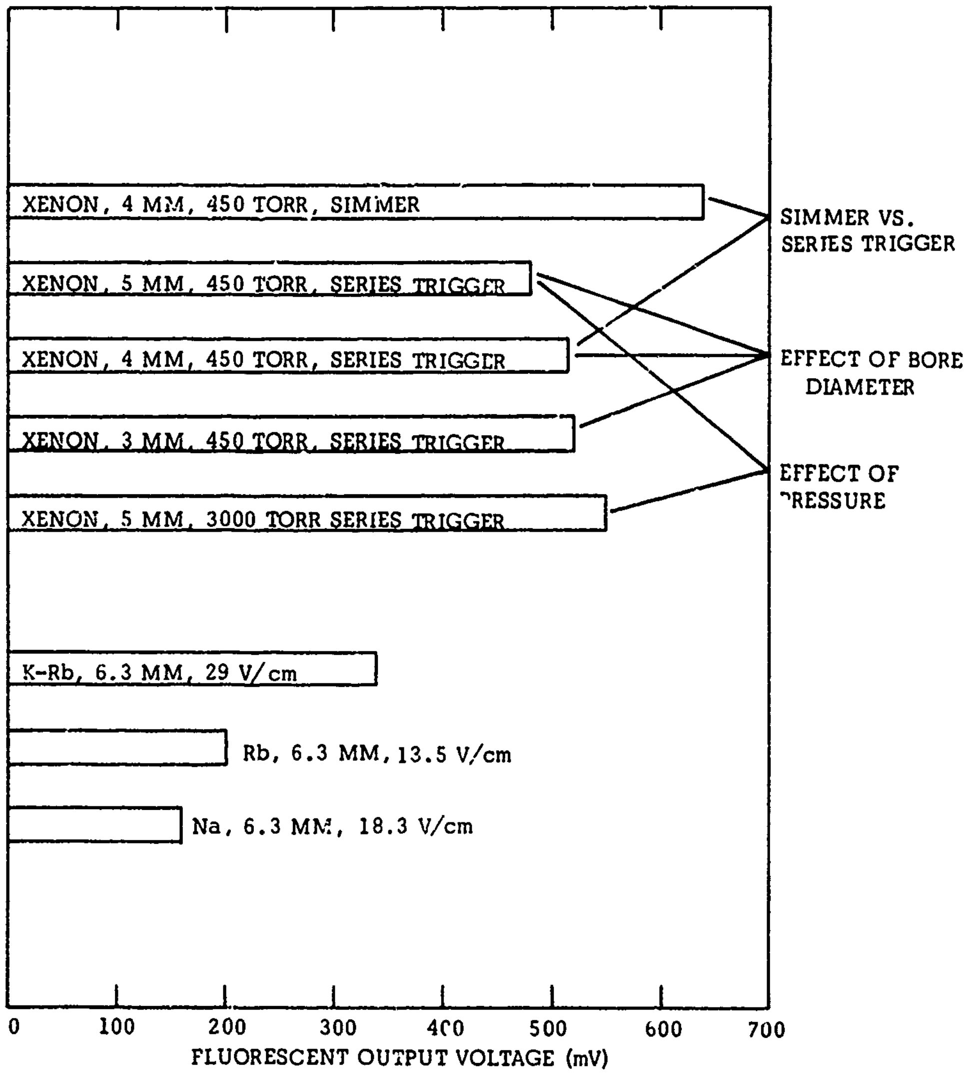


FIGURE 28. Ho:YLF FLUORESCENT OUTPUT VOLTAGE OF Ho:YLF SAMPLE WITH VARIOUS LAMPS (15 JOULE, 220-270 MICROSECOND PULSES)

4378